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Building Ventilation and Indoor Air Quality: The Impact of Urban Air Pollution - A Review.

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SUMMARY

This review examines the available information relating to the ingress of external pollutants into naturally ventilated buildings. It is part of a project whose longer term aim is to provide guidance on ventilation strategies for naturally ventilated buildings in polluted urban areas. The purpose of the review is to guide this project. It covers current ventilation strategies, existing measurements of internal/external pollution levels, urban air quality and long term air quality strategies, building ventilation and the dispersion of pollutants around buildings as they affect the ingress of pollutants.

At present, there is no formal advice on ventilation strategies to minimise the ingress of pollutants into buildings located in urban areas. The use of natural ventilation for buildings in such areas is to some extent affected by this deficiency and there is a tendency to prefer forced ventilation as an 'improved' option. In practice this need not be so.

Adequate guidance cannot be developed without an understanding of .

- Typical pollutants, their sources, how they disperse in urban areas and the concentration patterns produced on building surfaces in urban areas.
- Surface pressures on buildings, ventilation and infiltration processes as experienced by a building in an urban area.
- The occurrence of common areas of high pollutant concentrations and surface pressures on buildings.
- The relationship between the indoor and outdoor pollutant levels.

Generally there are significant information deficiencies in all these areas for the present application. Part of this is due to the multi-disciplinary nature of the application, for which none of these fields has a specific remit. For example, there are no identical experiments measuring both pollutant concentrations and wind pressures on the surfaces of buildings. The two specialisms are quite separate and have little intercommunication. Similarly, the problems of internal and external pollution levels tend to be considered separately, with little intercommunication.

The review confirms the need for the investigatory part of the project, which is to monitor internal/external pollution levels and carry out a common experiment looking at pressures and concentrations on the surfaces of buildings in urban arrays.

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1. INTRODUCTION

Fresh air for the ventilation of buildings is essential in order to provide an acceptable indoor environment in terms of both indoor air quality and thermal comfort for the inhabitants and in preventing a variety of problems such as condensation within the structure. The term 'fresh' in this context implies an air supply largely free from the internally generated contaminants that are traditionally of most concern; for example, water vapour, carbon dioxide (CO_2), odour, VOCs from furnishings and ozone from printers and photocopiers. However, in many cases the external air supply may carry a variety of contaminants of its own whose introduction to the internal environment by ventilation is undesirable. These include the conventional air pollutants, for example nitrogen and sulphur oxides, ozone and inhalable particles, as well as nuisance contaminants, such as dust and odour. This problem is most common in the larger urban areas where external pollution levels tend to be relatively high.

It is often considered that natural ventilation cannot provide adequate indoor air quality in buildings located in highly polluted surroundings. The use of mechanical ventilation and air-conditioning to 'clean' the incoming air is therefore favoured especially because of increasing concerns about the ingress of contaminants into buildings from external pollution sources such as those from vehicle emissions, building ventilation exhausts and boiler flues. However, in practice effective abatement rarely extends beyond some limited particle filtration, any reductions in other contaminant levels in the ventilation system being largely adventitious (due, for example, to attenuation by the building fabric). Also, studies (Morris (1985) and Kukadia et al (1996)), have shown that air-conditioning can generate its own pollution problems, for example, cross-contamination between ventilation exhausts and inlets which often raise pollutant concentration levels to values above those which are regarded as being acceptable. In addition, there have been long-running concerns regarding the incidence of Sick Building Syndrome in air-conditioned buildings.

There are significant advantages to the use of natural ventilation in urban areas if this can be achieved without ingesting excessive levels of external pollutants. In comparison to natural ventilation, mechanical ventilation has high operating costs and energy consumption, leading to higher CO_2 emissions. The contribution of building-related energy use to overall CO_2 emissions is considerable, estimated at 2,900 PJ (about 50% of the total). This has led to building designers being encouraged to design and construct energy efficient buildings suited to natural ventilation. Also, in temperate climates, naturally ventilated buildings can be designed to provide year round comfort, with good user control, at minimum capital cost and with negligible maintenance. Due to these reasons and to occupant preference (Ellis (1994)), ventilation by natural means is becoming a preferred option for buildings in general. Already it is being considered as a viable option in many new buildings in the UK especially in rural and suburban areas. Examples are given in the recent CIBSE Application Manual AM10 (CIBSE (1997)) on 'Natural Ventilation in Non-Domestic Buildings'. Furthermore, there are many older buildings (especially listed buildings) in urban and city centres which are naturally ventilated by default.

In these circumstances, the effective ventilation of buildings ought to be the subject of careful design in order to minimise the combined effects of contaminants from internal and external sources. At present this process is rarely carried out with any thoroughness in buildings on sites where external contamination levels are high. The main reason for this is that there is very limited formal advice, and little research data, on designing ventilation systems to avoid or minimise the effects of external contaminants. There is a growing interest in this subject and some work has been carried out (Philips et al (1993), Yocum (1982), Ekberg (1994), Trepte (1988), Kukadia et al (1996)). There is also a useful and interesting annotated bibliography of papers relating to air intake contamination and positioning by Limb (1994). However, in general internal and external contamination problems have been treated as separate entities and there is still a lack of fundamental understanding of the interactions between the indoor and outdoor environments, ventilation requirements and the effect that externally generated pollutants have on the indoor environment.

In the UK, advice on natural ventilation is currently available from a variety of sources, (for example, BS 5925 (1992), CIBSE Guide A (1986), CIBSE AM 10 (1997)). This is, at present, mainly concerned with the processes involved in designing for natural ventilation without any detailed reference to the ingress of external pollution. Thus, for example, the AIVC 'Guide to Energy Efficient Ventilation' (AIVC (1996)), makes only passing reference to natural ventilation being unable to deal with externally generated contaminants. Similarly, the CIBSE Applications Manual AM10 on 'Natural Ventilation in Non-domestic Buildings' devotes only a few paragraphs to the problems of air quality. It also implies that in situations where external pollution levels are high, natural ventilation is inappropriate. Figure 1, taken from Figure 1.17 of this manual, is intended to illustrate this point. Although there are circumstances in which the principle illustrated may be true, it is not universal and there ought to be good opportunities to design effective natural ventilation systems in buildings in polluted urban areas which minimise the ingestion of external pollutants. Both the dispersion of pollutants around buildings and the variety and positions of pollutant sources are considerably more complex than Figure 1 implies and there are circumstances where the implied advantage of mechanical ventilation in Figure 1 would be reversed.

In practice, internal contamination of buildings from external pollution sources depends upon both the ventilation and the pollutant dispersion processes around the building. For naturally-ventilated buildings, it is the combined distribution of both pressure differences between the inside and outside of the building and contaminant levels around the building that is important in generating the internal contamination levels. Regions of high pressure differences combined with high external pollutant concentrations will give regions of high probable ingress of contaminants and hence lead to greater internal pollutant concentrations.

The processes that generate both pressure and contaminant concentration patterns on buildings are complex and are affected by the surrounding structures as well as by the size, shape and orientation to the wind of the building itself. Contaminant concentration patterns are also affected by the types, positions and distances of the variety of contaminant sources to which the building will be exposed. Thus, both the layout of the urban area and the distribution of contaminant sources within it are important factors in the processes which govern internal contamination levels. The contribution of different sources (both in spatial and temporal scales) as experienced by a building in an urban location has been reviewed by Hall et al (1997) and will be discussed in greater detail later.

Although both wind pressures and pollutant levels around buildings have been the subject of much previous investigation, most of this has been concerned with isolated structures. The behaviour of buildings in urban areas, where they are closely surrounded by other buildings, has received far less attention, especially with regard to the dispersion of contaminants around buildings. Most work of this sort has been mainly concerned with specific applications and there are relatively few generic studies. In addition, there has been almost no consideration given to the combined effects of pressure and concentration distributions in this type of application, which is required for the present programme. Overall, the wind pressure and pollutant dispersion specialisms have had little intercommunication.

In order to be able to develop effective natural ventilation guidelines, information on and an understanding of the following is required:

- Typical pollutants, their sources, how they disperse in urban areas and the concentration patterns produced on building surfaces in urban areas.
- Surface pressures on buildings, ventilation and infiltration processes as experienced by a building in an urban area.
- The occurrence of common areas of high pollutant concentrations and surface pressures on buildings.
- The relationship between the indoor and outdoor pollutant levels.

The present research programme, of which this review is part, is concerned with providing essential basic information and guidance on these matters. The programme covers field measurements of internal/external pollution levels, small scale wind tunnel measurements of the combination of concentration and pressure on building models in urban arrays and the collation of this data into effective guidance. This review is an initial investigation of the available information on these topics and the degree to which it can be used for these purposes.

2. VENTILATION STRATEGIES AND INDOOR/OUTDOOR POLLUTION LEVELS

2.1. Background

In recent years, there has been considerable interest in the effect of external pollution on the indoor environment, relationships between indoor and outdoor pollutant levels and the factors that influence such relationships. There have also been measurements of indoor and outdoor pollution levels in a number of countries. Yocum (1982) gives a very good review of the research carried out in this area up to that date and remarks that 'However valuable each set of data might be to the aims of each study, the overall picture is one of significant fragmentation and duplication of effort'. The intervening period has seen little change in this approach. At present there is only limited work on either ventilation strategies or measurements of internal/external contaminant levels. However, there is a comprehensive annotated bibliography of papers on air intake contamination and positioning by Limb (1994) which gives information on work to 1994 in this area.

2.2. Ventilation Strategies

Traditionally, mechanical ventilation and air-conditioning have been used for buildings in urban areas to clean the incoming air. However, studies by Morris (1985) and Kukadia et al (1996) have shown that these may not necessarily be any better in providing cleaner air than naturally ventilated buildings. What is important is a well thought out ventilation strategy which considers the local pollution sources (traffic, boiler flues, building exhausts etc.), and the proximity of the building in relation to the wind and its surroundings. This is hardly ever done in any thorough way. Figure 2, reproduced from Kukadia et al (1996), shows the importance of ventilation inlet siting. The figure shows measurements of nitrogen dioxide concentrations inside and outside two buildings. The high peak in concentration for the mechanically ventilated building is a result of the ingestion of the dispersing plume from a nearby gas-fired boiler.

There have been a number of studies of this sort. Yocum (1982) pointed out that the indoor/outdoor air quality relationship is a complex function of several factors including outdoor air quality, meteorology, permeability of structures, pollution depletion mechanisms and ventilation. Trepte (1988) noted that the pollutant concentration in the indoor air is a function of the air change rate in a building. Figure 3 (taken from this work) shows a typical response of the indoor environment to transient outdoor pollution. The indoor pollutant concentrations rise as the outdoor air enters the building and continue to do so for as long as the outdoor concentrations are greater than those indoors. However, when the outdoor values fall below that of the indoor concentrations, the indoor values will decay at a rate which is dependent on the air change rate.

Based on this, Trepte recommended that during the occurrence of high external pollution episodes, the air change rate should be minimised to give a slow rise of external pollutant in indoor air and suggested appropriate methods, such as switching off mechanical ventilation units and closing windows. These would be activated once the outdoor concentration level dropped below the indoor levels. If the air change rate could not be minimised he recommended filtering, scrubbing and catalytic elimination of pollutants (a high-cost list of options). The associated indoor concentrations of CO_2, humidity and other related factors above the normally applicable criteria must then be accepted for short periods.

Ekberg (1994) in his thesis ('Airborne contaminants in office buildings: Some aspects of factors influencing the indoor air quality') reported findings from monitoring the activities in a number of office buildings. He noted that the location of air intakes is important in supplying ventilation air to a building, that pollutant concentrations may be considerable at roof levels of four to five storey buildings and commented that air intakes should preferably be placed on the facade away from polluted streets. He suggested that during high pollution episodes the air flow rate be reduced temporarily and indicated that by doing this peak concentrations could be reduced by between 20% and 50%. Where a building is close to streets with heavy traffic, he suggested filtration for mechanically ventilated buildings.

In the same way, Ajiboye et al (1997) proposed that, during pollution episodes, inlets are closed or fan assisted ventilation utilised which makes use of filters to clean the incoming air. Similarly, Fletcher (1997) suggested that 'full recirculation' is preferable for short periods when the outdoor air is polluted. O'Sullivan and Oreszeczyn (1992) suggested similar strategies for museums and galleries. Kruger (1994) also pointed out that the location of air intakes is important in relation to outdoor pollutant sources.

Rubino et al (1995) in their studies of an air-conditioned building in Milan remarked that the indoor air quality could not be improved by simply changing the position of the supply point from the ground level to the top of the building since only a limited reduction in pollution levels is achieved. What is more important is the global air quality of the city, in which case only the daily schedule of functioning of the HVAC system can be exploited.

Perhaps the only published work on the calculation of the relationship between indoor and outdoor concentrations is that reported by Ekberg (1994), who developed a mathematical model for this purpose based on the mass balance equations. This could be used when analysing monitored contaminant concentrations to obtain detailed information on the effect of indoor sources and sinks.

2.3. Measurements of Internal/External Pollution Levels

Weschler et al (1989) reported that ozone concentrations inside buildings tend to follow outdoor levels but that the concentrations are as low as 20% of those outside, while Cano Ruitz et al (1992) noted that indoor levels of ozone can be reduced by making the building envelope airtight and closing windows to reduce air change rates. They also concluded that external ozone decayed rapidly while flowing through some types of building fabric and on indoor surfaces. However, Phillips et al (1993) stated that indoor pollutant concentrations could be up to 80% of the concentration measured outdoors and in some cases mean indoor values can greatly exceed outdoor values.

It must be noted here that in the longer term internal mean pollutant concentrations cannot normally be higher than external mean values. However, there can be large short term fluctuations in pollutant concentrations around a building and, because of the different time scales associated with these fluctuations and with the ventilation rates of buildings, it is possible in the shorter term for pollutant concentrations to be higher inside the building than outside. Also, the choice of internal and external monitoring sites can be critical if there are large variations in pollution levels around the building. In the case of Phillips et al's work, measurements were carried out at one point externally (as is most commonly done) and this single measurement may not have been representative of the general concentration in the outside air. Phillips et al also pointed that ventilation is an important controlling factor in the outdoor/indoor pollution relationship.

O'Sullivan (1997), measured indoor and outdoor levels of CO in London, and his work has been summarised by Liddament(1997). O'Sullivan concluded that kerbside CO levels were usually greater than those found indoors and that inside the building the levels reduce with height and distance from open windows.

Kukadia et al (1996, 1997a, 1997b) have monitored a number of naturally and mechanically ventilated buildings in urban locations to determine the effect of external pollution levels found indoors. Their results showed that in general, the outdoor pollutants (CO, NO_2 and SO_2) were attenuated by the building envelope and the rapid fluctuations seen in the external concentration levels are not seen indoors. Figure 4, from Kukadia et al (1996), shows an example of this behaviour. Indoor pollutant concentrations followed the trend of external concentrations but the transient external peaks were halved in magnitude by the time they reached the indoors in some cases.

Figure 5 shows another example (from Kukadia et al, 1997b). In this case, air intake was from the courtyard side of the building away from the busy roadside. Internal concentration peaks of carbon monoxide in the offices were reduced by up to 30% over those occurring externally. Despite this particular example, this may not always be the case and courtyards may not always be good places for the location of ventilation inlets. Recent measurements by Hall et al (1998) have shown courtyards to be poorly ventilated spaces where self-contamination (by use as car parks for example) may lead to high local pollution levels.

Much of the work described above has been ad hoc, over short time periods of about a week and averaging times of about an hour. The longest by far, is of 60 days (Rubino et al (1995)). There is apparently no data in the literature on long term simultaneous internal and external pollution measurements, covering the various seasons of the year. This information is necessary as the characteristic cycle times of weather and pollution patterns are one year. This thus represents the minimum period required to obtain a representative sample. Without such data it is not easily possible to develop guidelines on ventilation strategies which are effective all year round.

3. VENTILATION OF BUILDINGS.

3.1. Background

The primary purpose of ventilation is to provide acceptable indoor air quality and adequate thermal comfort, thereby protecting occupants from adverse health effects. It is the means by which 'fresh' air is introduced and circulated throughout the building and by which contaminated or 'stale' air is removed or diluted. Adequate ventilation is therefore essential for the health, safety and comfort of building occupants, but excessive ventilation leads to energy wastage and sometimes discomfort. An optimum balance should be achieved between the indoor air quality, energy conservation and associated environmental issues and the necessary ventilation requirements for the well-being of occupants in buildings.

In a naturally ventilated building, air enters either by design (for example, through openable windows or wind towers) or adventitiously from uncontrolled leakage (infiltration) through cracks and gaps in the building fabric. Good ventilation design needs to be based on minimising infiltration by retaining an airtight building envelope and providing controlled ventilation as required. For a successful natural ventilation strategy, the three critical issues of:

- Infiltration and building tightness,
- Adequate (optimum) ventilation and
- Natural ventilation design,

need to be considered in an integrated manner in the building design.

This section reviews the general principles of natural ventilation and air flow rates through buildings and any guidance that is available in terms of ventilation and airtightness requirements and natural ventilation strategies for buildings in urban areas.

3.2. Infiltration and Building Tightness

3.2.1. Minimising Infiltration

Infiltration is the uncontrolled flow of air through gaps and cracks in the fabric of the building and is a measure of its leakiness, or airtightness. It is driven by pressure and temperature differences between the inside and the outside of the building and is highly sensitive to variations in external wind speed and temperature. Infiltration may significantly increase heat losses and can depress comfort levels by allowing unwanted draughts and cold spots.

In the present context, improved airtightness of the building fabric can minimise the ingress of outdoor contamination. It has been shown that airtight envelopes and closed windows significantly reduce the infiltration of external ozone in built-up city centres (Cano-Ruiz, 1992). Thus, improving the building envelope airtightness is a particularly attractive solution for buildings located in cities where external pollution levels are high (O'Sullivan, 1992). Thompson (1978) recommended that "the proportion of dirt reaching exhibits in a museum should be well below 5% by weight of outside levels" and that gaseous pollution should also be controlled, with ozone reduced to trace levels and sulphur dioxide and nitrogen dioxide reduced to no more than 10 $\mu g/m^3$. Without reducing air infiltration, these conditions will not be met in most historic buildings.

Typical air infiltration rates for buildings in various countries are shown in Figure 6, taken from Perera and Parkins (1992). The figure shows that leakage rates in the average UK office building are twice that of an average North American or Swedish building. However, specific examples such as the purpose-built Building Research Establishment (BRE) Low Energy Office have shown that it is possible to construct airtight buildings in the UK if due attention is given to good practice (Crisp, 1984).

Approximately three-quarters of air leakage may be through hidden paths rather than through clearly identifiable gaps and cracks in the building envelope. Although some benefits can be obtained by improved sealing in existing buildings, post-construction remedial measures often have only a minimal effect on already leaky buildings. It is thus more effective to design and construct tighter buildings than to carry out post-construction tightening.

There is clearly considerable scope for improving airtightness in existing UK buildings. Brundrett (1997) confirmed this in a review of recent data gathered by BRE and Building Services Research and Information Association (BSRIA), some results of which are shown in Figure 7. This found that 75% of the offices investigated were classed as being 'leaky'. Other field studies by Perera (1991, 1992) have shown that infiltration in a medium-sized office with a leaky envelope can be three times that of an equivalent building with a tighter envelope. In terms of space heating requirements during the heating season, uncontrolled infiltration is estimated to represents an energy loss of about 220 GJ (one third of the total enemy requirement) compared with about 70 GJ (one seventh of the total) for an airtight building.

3.2.2. Guidelines on Airtightness

Despite the practical importance of airtightness in building envelopes, the UK currently has no mandatory requirements for post-construction compliance testing. However some elements of the UK industry are setting voluntary standards as part of the commissioning process. The simplest standard for an 'airtight' building specifies that the whole building leakage should not exceed 5 m^3/h (per m^2 of permeable envelope area) for an imposed pressure differential of 25Pa across the envelope.

The revised 1995 Edition of Approved Document Part L (Conservation of Fuel and Power) of the Building Regulations for England and Wales (1995) contains provisions for reducing air leakage at windows and doors and through the building fabric. To support this, BRE have produced a guide giving advice on designing for improved airtightness in office-type buildings (Perera, 1994). Other design information from the Energy Efficiency Office (1993) is also available for industrial buildings.

The BRE guidance document emphasises that good constructional practice is the key to a tighter building. In the UK, there are good examples of tight buildings constructed according to these principles; eg. the purpose-built BRE Low Energy Office and the low-energy housing development in Orkney (Scivyer, 1994).

Following a study in 1995 of existing office buildings, BSRIA recommended that all new buildings should have an air leakage no greater than 5 m^3/h (per m^2 of permeable envelope area) at 50 Pa pressure difference (Brundrett et al, 1997). In 1997, the CIBSE issued guidance in the form of its Applications Manual AM10, which sets a value for airtightness of 7.5 $m^3/h/m^2$ or lower at a pressure difference of 50 Pa across the structure. Also, there is currently an initiative in progress on this matter, carried out in partnership between CIBSE, BRE and BSRIA. Its aims are to produce guidance on recommended test procedures and test standards; seek compulsory pressure tests for new buildings; set a maximum air leakiness standard for all new buildings and collaborate with other countries to work towards an international standard.

3.2.3. Measurement of Airtightness

The 'fan pressurisation' method (Stephen, 1988) currently gives the most direct way of measuring and characterising the airtightness of the building envelope. This involves sealing a portable fan into an outside doorway and measuring the air flow rates required to maintain a series of pressure differentials across the envelope. Over the last decade, the use of this technique for private dwellings has increased, but it is only recently that appropriate equipment has been developed for testing larger, non-domestic buildings and which is commercially available (Perera, 1989).

3.3. Ventilation Requirements

A correct balance has to be obtained between energy efficiency and the necessary ventilation requirements for the well-being of occupants in buildings. To do this, it is important to identify the role played by ventilation with respect to:

- Health - *to meet requirements for respiration and to dilute and remove contaminants.*
- Safety - *mainly to minimise the risk of explosion from flammable gas releases.*
- Comfort - *mainly relating to odour and overheating in the summer and to excessive cooling in the winter.*

Associated with each is an energy cost, either for space heating in the winter or, in certain cases, for cooling in the summer. The basis of good design is to identify the requirements that need to be satisfied and to then provide the necessary 'fresh' air ventilation in an appropriate and controlled manner.

Health Criteria

Ventilation necessary to satisfy health criteria is mainly set by the requirements for:

- Human respiration.
- Dilution and removal of contaminants generated within the occupied space.

Common pollutants generated within buildings can include the naturally occurring gases (for example, carbon dioxide, ozone, water vapour, methane), products of combustion (for example, carbon monoxide, oxides of nitrogen and sulphur), volatile organic compounds (for example, formaldehyde) and particles and fibres. Environmental tobacco smoke (ETS) is also considered to be a pollutant.

It must be noted that no guidance is given or mention made of ventilation requirements for the dilution or removal of pollutants generated externally and transported into the indoor environment via openings and by infiltration. This is due mainly to the lack of information in this area and the usual presumption that the outdoor air is 'fresh'.

Safety Criteria
Safety criteria relate mainly to eliminating or minimising the risk of explosion resulting from releases of flammable gases and vapours, for example methane. The risk levels are set by the higher and lower explosive limits; values for which are published by the UK Fire Protection Association.

Comfort Criteria
Current information on the ventilation requirements necessary to satisfy health and safety criteria is largely adequate. However, comfort criteria are more complex and need to take account of,

- odour
- metabolic CO_2
- tobacco smoke
- summer overheating
- winter cooling and draughts

Odour
Because of the effects of inurement, (the deadening of the nose over time to odours), the perception of odour requires regular changes in level.

Work in setting ventilation rates to control odour has been carried out by Fanger and others and is summarised by Parine (1994). The 'olf' and the 'decipol' were developed as a result of this work. The olf is defined as the unit of emission of 'air pollutant (bioeffluent) from a standard person'. The decipol is defined as the pollution caused by one standard person (1 olf) ventilated by 10l/s of unpolluted air and is a measure of perceived air quality. However, there is considerable controversy and scepticism about this approach (Oseland, 1993) and the validity of this procedure is still considered doubtful.

Metabolic CO_2
Human occupation of buildings gives rise to increased internal levels of CO_2 above the typical atmospheric level of about 350ppm (levels are a little higher in urban areas due to CO_2 from combustion processes). Human metabolic effects start to occur at concentrations of about 1000ppm and the HSE Occupational Exposure Limits are 5000ppm (Time Weighted Average, 8 hour) and 15,000ppm (Short Term Exposure Limit, 10 min). Normal ventilation practice is for levels to be kept below 1000 ppm and in practice these seem rarely to increase beyond this level. In terms of external contamination of ventilation air, the CO_2 levels in urban areas are insufficient to affect internal levels significantly beyond those resulting from normal practice.

*Environmental Tobacco Smoke (*ETS)
Environmental tobacco smoke affects both those who smoke and also those who are exposed to the combustion products of other smoker's tobacco. Neither the WHO nor the US Environmental Protection Agency has a lower limit for ETS, since there is sufficient evidence that tobacco smoke is carcinogenic at all levels. This has led to all US Federal and Government buildings imposing a ban on smoking, a trend that is spreading into commercial buildings. The UK governments Code of Practice in Public

Places (1991) gives suggestions on how exposure of the public to ETS can be minimised and provides guidance on suitable smoking policies for public places. Essentially, the recommendation is that 'no-smoking' should be the norm, with smoking allowed only in specially provided areas or rooms.

Summer Overheating

Buildings are subject to overheating from a number of sources both external (solar gain) and internal (people, lighting, IT equipment etc.). In the UK however, outdoor temperatures are generally at levels which should not cause problems of overheating. Usually excess internal heat gains can be removed by ventilation but there is a limit above which increasing ventilation rate has little or no added benefit. This limit is of the order of 5 air changes per hour in a typical cellular single-occupancy room. Generally, the natural air flow for cooling will be significantly higher than that required for air quality control and ventilation can be achieved by opening windows.

Ventilation during the night can be used to cool the building structure and so limit the temperature rise during the following day. The effectiveness of night cooling depends on the internal/external temperature difference as well as on the thermal characteristics of the building. A simplified design tool for night cooling (Tindale et al (1995)) has been developed which enables designers to assess the viability of such strategy and Kolokotroni et al (1997) have reported that night ventilation is an economically worthwhile strategy even in conventional buildings with lightweight internal structure.

Winter cooling and draughts

In the winter, any fresh air beyond that required for controlling indoor air quality incurs an energy penalty. Heat losses and draughts can be minimised by making the building envelope airtight. Openable windows need to be well sealed when closed to avoid infiltration energy loss. Local radiant heat loss and down-draughts from large areas of glass can be minimised by using double or triple glazing, insulated blinds and low-level heating. To shelter frequently used external doors from prevailing winds, draught lobbies can be provided.

To provide the winter ventilation requirement of 5 $l\ s^{-1}$ per person, installation of background ventilators, such as 'trickle' ventilators, is generally recommended as these will provide fine control of ventilation flows as well as preventing cold draughts. The Approved Document Part F (Ventilation) (1995) provides guidance on the use of permanent background ventilators, (with an openable area of 400 mm^2 per m^2 of floor area) which should be adjustable and located, typically 1.75 m above floor level. This is to avoid discomfort due to cold draughts and prevent the ingress of rain.

The CISBE Guide A1 (1986) gives recommended temperatures and outdoor air supply rates for various types of building. For example, it recommends that the temperature range for sedentary occupations should be 19°- 23°C.

3.4. Guidelines for Ventilation

3.4.1. Background

In most guidelines stating ventilation requirements, the use of fresh air is always emphasised, yet no provisions are made or guidance provided in ensuring that only fresh air enters any building. The accepted composition of 'fresh' air is 21% oxygen, 79% nitrogen and a carbon dioxide level of about 350 ppm in country areas. In built-up areas, however, the level of CO_2 is higher primarily as a result of fuel combustion (for transport, heating and industrial purposes). Also as mentioned earlier, in urban areas, the incoming 'fresh' air may also be contaminated by pollutants, such as carbon monoxide, oxides of nitrogen and sulphur, smoke and particles such as lead oxide. Most UK guideline documents refer to fresh air ventilation requirements for buildings in general and do not attempt to address the particular issue of external air quality in heavily polluted urban areas. In fact, the situation is similar internationally. A very good summary and comparison of international ventilation and airtightness standards, codes of practice and regulations is given by Limb (1994).

3.4.2. Prioritising Requirements

An over-riding principle in 'ventilating right' is that ventilation should be for people - not for the building. A common misconception is that dilution by ventilation is the only way to remove harmful contaminants from within the occupied space. The UK Committee on Substances Hazardous to Health (COSHH) lists the following methods (in order of preference) to ensure maintenance of good indoor air quality (Youle, 1991):

- Eliminate the substance.
- Substitute the substance for another less hazardous.
- Enclose the process.
- Partially enclose the process and provide local extract ventilation.
- Provide general (dilution) ventilation.
- Provide personal protection.

In the office environment, generation of internal pollution should either be avoided (eg. low-emitting furnishings and carpeting) or controlled locally (eg. by local extract ventilation near photocopying machines). If this strategy is followed, ventilation through 'fresh' air is then only needed to:

- Provide sufficient oxygen for breathing.
- Dilute body odours to acceptable levels.
- Dilute to acceptable levels the concentration of CO_2 produced by occupants and any combustion processes.

Consequently, the following fresh air levels of ventilation per person are recommended in the BRE Digest 399 (1994):

- 0.3 l/s as the minimum necessary to provide oxygen for life.
- 5 l/s to satisfy the current CIBSE (Chartered Institution of Building Services Engineers) recommended minimum ventilation rate.
- 8 l/s as identified in the 1995 edition of Building Regulations Approved Document (AD) Part F (Ventilation) for England and Wales provision for 'rapid' ventilation (ie. to rapidly dilute when necessary, pollutants produced in habitable rooms).
- 16 l/s in the same Regulation's provision for rooms designed for 'light' smoking.
- 32 l/s to minimise the effects of 'heavy' smoking.

Thus, depending on the proportion of occupants smoking, ventilation requirements may vary considerably. Policies for minimising Environmental Tobacco Smoke has already been discussed in section 3.3.

3.4.3. Mechanisms of Natural Ventilation

Natural ventilation is the intentional provision of outdoor air into a building through purpose provided openings. It relies on air flow through the building driven by the combined effect of wind and temperature differences between the inside and outside. It is dependent on the building height, height between ventilation openings, internal resistance to airflow, location and flow resistance characteristics of the building envelope openings, the local terrain and the immediate surrounding structures. Figure 8 (taken from Liddament (1996)) shows a diagram of the two types of airflow in natural ventilation.

Much of what is described below has been summarised from the following documents which represent UK practice in natural ventilation: CIBSE Guide A, CIBSE AM10 on 'Natural ventilation in non-domestic buildings', BS 5925, AIVC 'A Guide to Energy Efficient Ventilation' and BRE Digest 399.

3.4.4. Calculation of Ventilation Rates

It is essential to calculate the optimum ventilation rate of a building to cater for acceptable levels of occupant comfort and adequate indoor air quality as well as for minimising ventilative heat losses and energy conservation.

For building envelopes, the relationship between ventilation flow Q through any openings (whether purpose provided ventilation or infiltration through cracks and gaps), and pressure difference ΔP across that opening can be given by the Power Law equation, which is,

$$Q = k \Delta P^{n}$$

where k = flow coefficient ($m^3 s^{-1}$ per m^2 of surface area at 1 Pa)
n = flow exponent.

The flow exponent, n, characterises the type of ventilation flow and varies in value between 0.5 for fully turbulent flow (as occurs through large openings) to 1.0 for laminar flow (as occurs in infiltration through small gaps. In general, n varies between 0.6 and 0.7 for infiltration through many building components (Orme et al, 1994). For most general calculations, a value of $n = 0.66$ is acceptable.

For large openings such as purpose provided vents, the value of n is usually about 0.5 and the air flow may be calculated approximately as an equivalent flow through an orifice plate, using the usual equation,

$$Q = C_d A \left(\frac{2 \Delta P}{\rho} \right)^{0.5}$$

where C_d = discharge coefficient
ρ = air density ($kg\ m^{-3}$)
A = area of opening (m^2)

The flow coefficient, k, is then given by,

$$k = \frac{Q}{\Delta P^{0.5}} = C_d A \left(\frac{2}{\rho}\right)^{0.5}$$

The pressure difference, ΔP is generated by the combined effect of wind and buoyancy forces and this needs to be determined and their combined effect used in order to accurately calculate ventilation rates.

Buoyancy (stack) driven ventilation: Temperature differences between the inside and outside air induce buoyancy forces and hence drive the ventilation process. Thus, if the air temperature within a building is higher than that outside (eg during the heating season), the temperature difference creates an air flow through openings in the fabric of the building. The warmer air inside rises and flows out of the upper parts of the building and is replaced by colder air entering the building near its base. The height at which the interior pressure equals the exterior pressure (ie inflow equals outflow), is called the neutral pressure level (NPL).

Calculation of the stack pressure, P_s, is based on the temperature difference between the two air masses and the vertical spacing between the openings. The governing equation is,

$$P_s = -\rho_o g 273 (h_2 - h_1)\left(\frac{1}{T_e} - \frac{1}{T_i}\right)$$

where ρ_o = density of the air at 273K (1.289 kgm^{-3})
g = acceleration due to gravity (9.81ms^{-1})
T_e = outdoor air temperature (K)
T_i = indoor air temperature (K)
h_1 = height of opening 1 (m)
h_2 = height of opening 2 (m)

Wind driven ventilation: As wind speed increases, pressure differences on the building faces increase and eventually any buoyancy-driven ventilation is replaced by wind driven ventilation. Figure 9, taken from Liddament (1996), illustrates this behaviour. The dividing windspeed between these two conditions varies, but is typically 2-3ms^{-1}. Differences between the wind pressures on the outside of the building and the internal pressure then drive the ventilation. The wind mainly induces positive pressures on the windward face and the downwind side of the roof, with negative pressures on the remaining faces and the upwind side of the roof. The internal pressure of a well-sealed building is close to the average over the external surfaces, but if there are significant openings (exceeding a few percent of the surface area) the internal pressure tends towards values at the openings. The air then enters openings in the building from the high pressure areas and leaves through the low pressure areas. Accurate information on surface pressures on the building is therefore required to enable ventilation rates to be calculated.

It has been found (BS 5295 and CIBSE Guide A) that, for any given wind direction, the pattern of flow around a building is virtually independent of wind speed, provided that the building has sharp corners. Therefore, the mean pressure generated at any point on the external surface is dependent only upon the dynamic pressure of the upstream wind and can be defined in terms of a dimensionless pressure coefficient, C_p, where,

$$C_p = \frac{(p - p_o)}{\frac{1}{2}\rho v_r^2}$$

and p = mean pressure at any point on surface of building,
p_0 = static pressure in undisturbed wind,
ρ = density and
v_r = mean wind speed at height equal to the height of the building under consideration.

Information on pressure coefficients on buildings is thus important for the present application, both for the determination of optimum ventilation rates for a building and for the effective development of ventilation strategies which minimise the ingress of external contaminants.

3.5. Building Pressure Coefficients for Wind Driven Ventilation

3.5.1. Background

Much of the pressure data that is currently available in the literature is intended for wind loading applications rather than for ventilation and is either for isolated buildings in open terrain (that is, fully exposed to wind from all directions), or individual studies of specific buildings in specific urban environments. There is limited systematic information on the effect of the surroundings on building pressures even though the majority of buildings are not fully exposed.

Most buildings are in urban locations and using values of C_p from information on exposed buildings leads to over-estimation of ventilation rates. Buildings in such areas may be sheltered by surrounding structures, such as other buildings, foliage and surface topography. This changes the local flow field around the building and hence the magnitude and distribution of the pressure coefficients.

In addition, the characteristics of the approaching wind, including the mean windspeed, turbulence and shear stresses affect the flow around a building. The mean velocity profile is often expressed by the Power Law equation,

$$U_z = U_m K z^a \quad (m/s)$$

where U_z = building height wind speed (m/s)
U_m = wind speed measure in open country at a standard height of 10 m (m/s)
z = building height (m)
K, a = constants dependent on the terrain

Values for the Power Law exponent, n, for different terrain roughnesses are given for the UK in BS 5925 (1991) and (Liddament, 1996) and are reproduced in Table 1.

It is important that the correct wind velocity (usually taken at the building height) is used for wind pressure calculation. The Power Law can be used to correct the meteorological wind speed (usually measured at a standard height of 10 m) to a wind speed at the building height in a given terrain roughness.

Table 1. Values of the Power Law Constants in the Mean Wind Profile Power Law Equation.

Terrain	Constants	
	K	a
Open flat country	0.68	0.17
Country with scattered wind breaks	0.52	0.20
Urban	0.35	0.25
City	0.21	0.33

3.5.2. Surface Pressures on Isolated Buildings

Although much of the work on pressures on buildings has been carried out for wind loading applications (for example, Newberry et al (1967), Hoxey and Moran (1983), Cook (1990)) there is also some information on pressures on buildings for the purpose of ventilation and infiltration estimates (Handa and Gusten (1981)). Most of this latter work is for specific buildings in specific environments and only a limited amount is useful in the present application.

Some of the most extensive systematic pressure measurements on isolated buildings have been those made by Akins, Peterka and Cermark (1979) who examined the effects of different boundary layer velocity profiles and wind directions (at intervals of 10°) and produced a single mean pressure coefficient for a given building side and wind direction.

The BRE Digest 346 (1989) on 'The assessments of wind loads Part 6: Loading coefficients for typical buildings' gives a very good summary of and guidance on pressure coefficients on isolated buildings. It provides data on pressure coefficients for the walls and roofs of sharp cornered buildings and outlines a procedure for rectangular buildings with flat, gabled or hipped roofs. It also comments that in principle the procedure may be applied to more complex shapes. Figure 10, taken from Hall et al (1995), shows an example of the distribution of C_p across warehouse buildings, derived directly from the BRE Digest.

3.5.3. Surface Pressures on Buildings in Urban Arrays.
A number of investigators (Piggins (1991), Walker (1992) and Liddament (1996)) have reviewed the literature and summarised the information in a number of publications. Piggins (1991) gives a comparison of the ventilation rates calculated using six different pressure coefficient data sets. Data from all the six sources (BRE, Wiren, Balazs, Akins et al, Gandemer and Bowen) was initially compared for an isolated building and then data sets from two sources (BRE and Wiren) were used for a comparison of the effects of differing surrounding building densities. The surrounding buildings were assumed to be of the same height as the building being modelled.

The estimated air change rate against wind speed for buildings of height to width ratio (L/W) of between 1 and 2 but with no surrounding buildings is shown in Figure 11. In general, the air change rates which correspond to pitched roofs (BRE and Wiren) are similar and higher than those for flat-roofed block-shaped buildings. Piggins concluded that 'despite the obvious differences of aspect ratios, roof pitches and terrain simulations between data sets, good general agreement was observed with results varying between +/- 13% of the mean'. The variation in air change rate with wind speed for the two data sets (BRE and Wiren) with the effect of surrounding buildings is shown in Figure 12. It can be seen that there is a clear and consistent agreement between the two data sets. Piggins noted that 'for simple ventilation rate estimations, careful selection of a data set from a broadly similar building and terrain would appear to be sufficient'.

Walker (1992), also gives a very comprehensive description of the factors (upstream flow, wakes, geometry, wind direction, building separation and shelter from several obstacles) that affect the pressure coefficients, C_p's of sheltered buildings by reviewing work to date in this area. The most relevant information for the present work is that summarised in his paper as follows:

Turbulent Scales: The effects turbulent scales of the approaching flow are complex and change pressure distributions in both time and space. Increasing turbulence and shear tend to reduce the value of C_p on a building and the reduction in upstream velocity from increased surface roughness due to the surrounding structures lowers the positive C_p's on an upwind wall.

Wind direction: Akins, Peterka and Cermark (1979) give examples of the variations in pressure coefficients with wind direction on an isolated building. Other data covering fewer wind directions may be found in ASHRAE (1989) and in Liddament (1986).

Walker gives a good summary of Wiren's (1985) work on the effect of wind direction on pressure coefficients on a building with identical buildings on either side. He emphasises that in this case, the building separation distance S (from wall to wall normalised by the building height, H) is an important parameter. For a value of S/H ~ 1.7, Table 2, below (reproduced from Walker), shows results of the effect of wind direction on shelter for C_p's on buildings in rows. The numbering conventions are shown in Figure 13. He also gives examples of the variation of C_p with wind angle for a sheltered and an unsheltered building for two walls (upwind wall (0°) and side wall (90°), which are reproduced in Figure 14. The greatest effect is when the wind blows along the row (at wind angles of 90° and 270°). More comprehensive examples of this data can be found in Orme et al (1994).

Table 2: Effect of Wind Direction on Shelter for Cps on Buildings in a Row (Wiren 1985). From Walker (1992).

Wind Direction	Wall				Roof	
	1	2	3	4	Front	Rear
Normal to wall 1	0.6	-0.7	-0.9	-0.9	0.2	-0.8
Normal to wall 3	-0.15	-0.15	-0.15	-0.15	-0.15	-0.15
Isolated building - normal to wall 1	0.6	-0.65	-0.85	-0.85	0.2	-0.8

Building separation: The work of Hussain and Lee (1980) has also been summarised and discussed by Walker in terms of three flow regimes for shelter arrays that depend on building separation. These are as follows:

1. Isolated roughness (S/H >2.5) - the buildings are far enough apart that each building acts in isolation.
2. Wake interference (2.5>S/H>1.5) - 'buildings are closer together and the separation bubble is not fully developed because the front separation region (leading horse shoe vortex) of the downwind building is met before reattachment.
3. Skimming flow (S/H> 1.5). - the separation bubble forms a stable vortex between the buildings. It must be noted here that the skimming flow is easily destroyed by variations in building height exceeding 10%.

In addition to this, Lee, Hussain and Soloman (1979) have defined the area of surrounding buildings whose positions exerted an influence on the values of pressure coefficients of the building under study. This is shown in Figure 15 and demonstrates the relative importance of upwind and downwind fetches and shows that the effect of buildings on either side is small. In addition, a prediction technique has been developed which enables surface pressures acting on a particular building situated within an array of similar low rise buildings to be estimated.

Table 3. The Influence of Building Separation on Surface Pressure Coefficients. (Wiren, 1985). From Walker (1992).

Separation S/H	Wall				Roof	
	1	2	3	4	Front	Rear
Isolated	-0.5	-0.5	0.6	-0.3	-0.4	-0.4
4.25	-0.4	-0.4	0.35	-0.25	-0.3	-0.3
3.4	-0.35	-0.35	0.3	-0.25	0.25	-0.25
2.55	-0.25	-0.25	-0.25	-0.2	-0.2	-0.2
1.7	-0.15	-0.15	-0.15	-0.15	0.15	-0.15

Wilson and Walker (1992) have shown that ventilation rates in terraced houses are reduced by a factor of three when the wind is parallel to the row of houses. A summary is presented, in Table 3, of Wiren's data for buildings in a row with varying separation with wind flow along the row parallel to walls 1 and 2. The numbering convention is the same as in Figure 13. This shows that the pressure distribution becomes more uniform as the separation is decreased.

Shelter from surrounding structures: In urban areas, a building may be surrounded by more than one structure and may be sheltered in the wakes of some of these. The form and relative size of a building is important since a large building will completely immerse a smaller building in its wake and affect the surface pressures comprehensively. Walker states that Wiren's data for examining building shelter is one of the most comprehensive of existing wind tunnel data sets since it includes a boundary layer with shear and turbulence together with pressure coefficients measured on each surface. Results from Wiren's work, in the context of the present study, have been summarised later in this report. Here, Wiren's data for buildings surrounded by uniform arrays of obstructions as summarised by Walker, are shown in Table 4. The numbering convention is again as in Figure 13.

Table 4. The Effect of Additional Sheltering by Surrounding Obstacles on Surface Pressure Coefficients. (Wiren, 1985). From Walker (1992).

Separation S/H	Wall				Roof	
	1	2	3	4	Front	Rear
Isolated	-0.5	-0.5	0.6	-0.3	-0.65	-0.65
1 ring, S/H = 1.7	-0.2	-0.2	0.15	-0.2	-0.2	-0.2
2 rings, S/H = 1.7	-0.2	-0.2	0.15	-0.2	-0.2	-0.2
3 rings, S/H = 1.7	-0.2	-0.2	0.15	-0.2	-0.2	-0.2
1 ring, S/H = 3.4	-0.35	-0.35	0.25	-0.3	-0.25	-0.25
2 rings, S/H = 3.4	-0.3	-0.3	-0.25	-0.3	-0.25	-0.25
3 rings, S/H = 3.4	-0.3	-0.3	-0.25	-0.3	0.25	-0.25

The results show that the immediately adjacent ring of obstacles dominates building sheltering effects, with buildings further away contributing little extra sheltering effect. Also there is little difference between the shelter provided by an array of buildings and buildings in a row when the wind is along the row. Doubling S/H confirms that only the closest obstacle has a significant effect on the building shelter.

Using the data from Wiren's work, Walker produced guidelines for estimating pressure coefficients in sheltered environments. These are as follows and are applicable to the present work in the absence of any other relevant data.

1. Assume that most buildings are in urban locations and have other buildings within two building heights in all directions.
2. The closest sheltering structures dominate the shelter experienced by a building.
3. The most appropriate pressure coefficients to use are taken from Wiren 1985 and reproduced by Walker, as shown in Table 4.
4. Buildings that are further apart or unsheltered have less uniform C_p's, as shown in Table 3.
5. To calculate C_p's for values of S/H not shown in the tables a linear interpolation between tabulated values may be used.
6. For building separations below the lowest values (S/H = 1.7) in the table use the lowest values.
7. For buildings with non-uniform shelter, Figure 14 can be used to estimate the change in C_p's on each wall.

Surface pressures on buildings for the present study: Although Walker has given a good summary of the factors that affect pressures on buildings in urban arrangements, the work of Bowen (1976) and Wiren (1980) is considered here in more detail with regard to distributions of pressures on building surfaces, which is required for the present study. Orme et al (1994) have produced a good summary of the wind pressure distributions from Bowen's work. An example of this is shown in Figures 16 and 17. The measurements are for a 1:400 scale model of a tall building with a flat roof, located in a rectangular array of flat-roof low rise buildings of 1/6 its height.

Wiren (1983, 1985) in his studies obtained the wind pressure distributions over a 1:100 scale model of a 1½ -storey single family house, surrounded by identical building models in various arrays. The model configurations studied are shown in Figure 18 and an example of the pressure distributions from three of these are shown in Figure 19.

Wiren also studied pressure distributions over a 1:100 scale model of a row of five 2-storey, flat-roofed terrace houses, surrounded by identical rows of houses in various regular arrays. Again the model configurations studied are shown in Figure 20 and an example of the pressure distribution is shown in Figure 21.

All the data from Bowen's work and Wiren's work has been brought together and tabulated by Orme et al (1994) for three types of building exposure. These are:

Open countryside - no obstructions - exposed buildings
Rural surroundings - some obstructions - semi-sheltered buildings
Urban - building surrounded on all sides by obstructions of similar size - sheltered buildings.

A typical example from this is given in Figure 22.

In addition to the above, there are some other individual papers of interest. Bauman et al (1988) measured pressures on arrays of long rows of low-rise buildings, mainly to investigate the behaviour of roof ventilators. However, the work also provided pressure coefficients on the faces of the buildings. They remarked that for closely spaced buildings it was difficult to generate sufficient pressure difference for cross-ventilation designs. Tsutsumi et al (1992) carried out wind tunnel studies of the pressures on low rise apartment buildings. Both normal and staggered grid layouts were used and the effects of wind direction were examined. The experiments provided pressure patterns on the building faces. Figure 23 shows examples of this data, which are pressure coefficient contours on the building faces for a normal array and varying building occupational densities and wind directions. One conclusion of the work was that pressure distributions become more uniform as the building occupational density increases.

A feature of urban areas is that the layout of the buildings is frequently non-uniform. Most systematic experiments on building pressures in urban areas use uniform arrays in order to avoid unnecessary confusion in the data. However, the effects of the non-uniformity of real urban areas need to be known. An important contribution to this matter is the random city experiments carried out at the University of Western Ontario. In these wind tunnel experiments a number of standard building shapes were placed at different sites in a randomly organised urban area model, so that the variation in pressure coefficients due to siting could be found. Some results of this work are summarised in three papers, by Ho et al (1990, 1991, 1992) and led to the determination of coefficients of variation of the peak pressure coefficients. Table 5 reproduced from Ho et al (1990) shows a summary of the results for buildings in isolation and within the random city.

Table 5. Coefficients of Variation of Pressure Coefficients on a Building Surface Inside and Outside the Random City.

Building Face	Random City				Isolated Building			
	Positive		Negative		Positive		Negative	
	open	sub	open	sub	open	sub	open	sub
ROOF								
All Area			0.78	0.72			0.73	0.70
Corner			0.72	0.65			0.72	0.69
Edge			0.71	0.65			0.61	0.56
Interior			0.65	0.69			0.61	0.56
WALL								
All area	0.86	0.72	0.71	0.62	1.14	0.90	0.90	0.74
Edge	0.91	0.75	0.73	0.64	1.26	0.94	0.87	0.77
Interior	0.84	0.70	0.60	0.52	1.10	0.88	0.85	0.64

Ho et al make a number of remarks about these results. Firstly, the values are large, the standard deviation of the fluctuation is of the order of 60-100% of the mean. Secondly, although differences between the building isolated and within the random city seem small, they arise from different causes. Those of the isolated building are due to the effects of wind direction, those for the building in the random city are due to the layout variations of the random city.

4.0. ATMOSPHERIC POLLUTION AND DISPERSION IN URBAN AREAS

4.1. Pollution in Urban Areas

The concentration of human activities into urban areas has resulted, almost by definition, both in their containing the majority of buildings and in being areas with high concentrations of polluting discharges. On this basis it must be presumed that the majority of buildings suffer at least in some degree from the ventilation contamination problems described in the introduction.

There are two main types of external airborne pollution which can cause building contamination problems. These are:

- Those causing nuisance.
- Those capable of generating adverse health effects.

The two most important nuisance pollutants, and by far the most common causes of complaint, are odour and dust, both directly detectable without instruments. Another, but less common, nuisance 'contaminant' is obscuration from visible condensed plumes with a high water content, mainly occurring in cold weather from hot, humid discharges (cooling towers, for example).

Similarly, there are a number of broad groupings into which man-made pollutant sources can be divided. The most important of these for the present purposes are:

- Road traffic
- Combustion plant running on conventional fuels
- Other combustion processes (for example, waste incineration, thermal oxidation abatement systems)
- Discharges from industrial processes
- Fugitive (adventitious) discharges from industrial processes and other sources
- Building ventilation exhaust discharges
- Domestic (mainly space heating)

Table 6 (below) shows typical figures for the relative scales of these emissions in the UK.

Of the source types, road traffic is distinguished by mobility, all the other sources are static. Vehicle emissions are also presently identified as probably the major local pollution source in urban areas (QUARG(1993)). However, it must be appreciated that other sources are often the principle component of the overall pollution level. Of the pollutant discharges from different sources, only those from combustion plant running on conventional fuels are relatively closely defined in quality and quantity. The other sources are usually only known approximately. This applies especially to odours, which are quite difficult to quantify. However, nearly all process discharges are now highly regulated and are authorised to operate under the Environmental Protection Act (1990) only on the basis of defined limits to their polluting discharges.

Table 6. The Main Sources of Pollutants - National Emission Figures taken from the DETR National Air Quality Strategy (1996).

Pollutant source	PM_{10} 1994	NO_x 1993	CO 1993	SO_2 1993	Lead 1994	Benzene 1993	VOC 1994	Butadiene 1993
Transport	29%	59%	90%	5%	64%	68%	35%	77%
Combustion	35%	24%	3%	92%	4%	5%	2%	-
Chemicals and fuels	-	-	1%	-	-	11%	25%	18%
Other industrial	24%	14%	-	-	27%	16%	25%	-
Waste	-	-	1%	-	4%	-	-	5%
Domestic/ Other	14%	3%	5%	3%	1%	-	13%	-

The other important distinction between different sources for the present purpose is the height of release. Discharges from road traffic are mostly (but not always) at the ground, while those from combustion and process discharges are (with a few exceptions) elevated above the local building heights. In the latter cases there is normally a regulatory requirement for minimum discharge stack heights to ensure that pollution levels at the ground from these sources are within acceptable guideline levels. Only some types of pre-diluted gas fired combustion plant exhausts are permitted to discharge below roof height. Fugitive and ventilation exhaust discharges are under no specific regulation and their heights and positions are largely arbitrary.

4.2. Guidelines on Outdoor and Indoor Air Quality

4.2.1. Guidelines on Outdoor Air Quality

There is a wide range of outdoor pollutants either known or suspected of causing health effects. Some have been the subject of attention for many years, for example sulphur and nitrogen oxides, ozone, black smoke, carbon monoxide and heavy metals (especially lead), while the significance of others has only been fully appreciated and subjected to serious investigation more recently, for example inhaled fine particles (including PM_{10}), benzene, 1-3 butadiene, PAH's and Toxic Organic Micropollutants (TOMPS).

The major air pollutants are generally already under high levels of regulation, which is tending to become more stringent with time. Over the past few years the UK Expert Panel on Air Quality Standards (EPAQS) has published recommended guideline concentrations for some common pollutants (carbon monoxide, nitrogen dioxide, sulphur dioxide, particles, 1,3 butadiene and ozone) found in urban areas. These guidelines have been produced in relation to exposure of the general populace. There is a discussion of the most significant pollutants, the general trends in air pollution and the longer term proposed regulatory plans in the UK National Air Quality Strategy (DOE(1996)). Table 3.1 from this document, which lists the major pollutants and their proposed exposure limits is reproduced here in Table 7. Some of these are regulatory limits and some advisory 'guidelines'. Many monitoring sites in urban areas still show regular exceedences of the various advisory guidelines and exposure limits by a number of the major pollutants. For example, in 1991 London experienced the most severe nitrogen dioxide pollution episode since regular monitoring began in 1971. The exceedences are published in the annual summaries of the National Network data (see, for example AEA(1997)).

Table 7. The Major Air pollutants and their Proposed Exposure Limits by 2005. (Reproduced from the UK National Air Quality Strategy (DOE(1996))

POLLUTANT	STANDARD concentration	 measured as	SPECIFIC OBJECTIVE to be achieved by 2005
Benzene	5 ppb	running annual mean	the air quality standard
1,3 Butadiene	1 ppb	running annual mean	the air quality standard
Carbon Monoxide	10 ppm	running 8-hour mean	the air quality standard
Lead	0.5 $\mu g/m^3$	annual mean	the air quality standard
Nitrogen Dioxide	104.6 ppb 20 ppb	1 hour mean annual mean	104.6 ppb, measured as the 99.9th percentile to be achieved by 2005*
Ozone	50 ppb	running 8-hour mean	50ppb, measured as the 97th percentile, to be achieved by 2005*
Particles - PM_{10}	50 $\mu g/m^3$	running 24-hour mean	50 $\mu g/m^3$ measured as the 99th percentile, to be achieved by 2005*
Sulphur Dioxide	100 ppb	15 minute mean	100 ppb measured as the 99.9th percentile, to be achieved by 2005*
ppm = parts per million; ppb = parts per billion; $\mu g/m^3$ = micrograms per cubic metre * these objectives are to be treated as provisional, as described above.			

For pollutants other than those in Table 7, there is currently, in the UK, no formal complete list of acceptable guideline concentrations of pollutants for the general populace. It has, therefore become common practice to use the only available complete list of exposure levels in the UK, the List of Occupational Exposure Limits issued by the Health and Safety Executive (HSE(1997)). These are commonly occurring pollutants in the workplace; however, the general populace may also be exposed to them after they are discharged. In the absence of any guidelines for the general populace, Technical Guidance Note (Dispersion) D1 by Her Majesty's Inspectorate of Pollution (1993) recommends that a level of one fortieth of the short-term exposure limit or the time weighted average (TWA) be used; if the pollutant is scheduled under the COSHH regulations and has a Maximum Exposure Limit (MEL), then a level of one hundredth of the MEL should be used.

In general there is little assistance in this area worldwide, with limited lists of guideline concentrations of pollutants being issued by some countries. However, comparison between them often shows large variations in their values. The guideline concentrations issued in the UK for the major pollutants follow European Community requirements. They mainly relate to background concentration levels of a few major pollutants and usually to longer term exposure levels, with shorter term limits being provided in some cases. The World Health Organisation (WHO)(1987) has published guidelines for some common pollutants; these are probably amongst the most extensively used.

Other guidelines which exist are those issued by the UK Department of the Environment, Transport and the Regions (DETR) and the US Environmental Protection Agency. The Tables in Appendix A, taken from AEA(1997), outline the various outdoor air quality guidelines and standards that are in use for some common pollutants.

4.2.2. Guidelines on Indoor Air Quality

Unlike the relatively highly regulated state of outdoor air quality, little exists worldwide on concentration guidelines and standards for indoor air pollutants. This seems surprising, since typically 90% of occupants' time is spent indoors. Although, there can be no doubt that exposure standards contribute to establishing legal guarantees, two major criticisms have been made against the setting of standards for chemicals (and micro-organisms) in indoor air (Seifert, 1992). These are,

- The existence of a standard favours the impression of having a limit below which there is no reason for concern.
- The enforcement of a standard is virtually impossible due to the large number of indoor spaces which would need to be checked.

In addition, Seifert argued that the large variety of conditions encountered inside buildings makes it difficult to define the boundary conditions to be associated with the standard. However, it is not clear why such a view should hold weight for the internal environment when it is not considered acceptable for either the external environment or the industrial workplace, where appropriate standards have been set as a matter of principle and practical application for many years.

Nevertheless, indoor air quality guideline values for some individual substances - either applicable to or expressly developed for indoor air - have been published by the WHO, The Department of National Health and Welfare, Canada (1987) and the Norwegian Health Directorate, 1990. Again, those set by the WHO are probably the most extensively used. ASHRAE 62-1995(ASHRAE (1995)) on Ventilation for Acceptable Indoor Air Quality gives guidelines and standards for some pollutants but the list is not very extensive.

Because of this lack of guidelines for indoor air, there has been a tendency to use the Occupational Exposure Limits issued by the UK Health and Safety Executive (HSE(1998)) for those contaminants that it covers. However, it is doubtful whether these limits are acceptable for most buildings. Formally, they are set as exposure limits for physically fit individuals in the industrial workplace, exposed for a nominal eight hour day, five day week. They thus exclude a number of sensitive groups; the old, the young, the infirm and those unusually sensitive to some contaminants, as well as anyone more permanently inhabiting a building. Most commercial buildings are occupied by a different, and probably more sensitive, cross section of the populace for varying time periods. Also, the general populace (which includes these more sensitive groups) have normal access to many buildings. In these circumstances a more stringent exposure limit ought to prevail and it would be more appropriate to use the, lower, external air quality guidelines set for exposure of the general populace.

4.3. Guidelines on Vehicle Emissions

The First Report of the Quality of Urban Air Review Group (QUARG(1993)) concluded that road transport was a major source of urban air pollution and that the proportionate contribution to emissions in towns and cities from the transport sector had increased in recent years due to its rapid growth. Declining emissions from other sources, notably domestic and light industrial coal burning, have resulted in road vehicles now accounting for 74% of nitrogen oxides, 94% of black smoke and 90% of CO emissions in London (Second QUARG Report (1993)).

As road traffic has increased, legislation has been progressively tightened in response to environmental and public concerns about associated pollution levels. Action has already been taken to reduce toxic emissions from vehicles. Originally, emission limits for motor vehicles were set by the United Nations Economic Commission for Europe (UNECE) and then introduced into European Community legislation. Over the last few years the European Community has set its own, more stringent, emission standards. The second QUARG report (QUARG(1993)), on diesel vehicle emissions, gives a good summary of guidelines and emission limits that are available for different types of motor vehicle.

The ingestion of vehicle emissions into buildings is currently a major concern, partly due to their proximity to many buildings. Also, as they are most commonly emitted at ground level, there is often a high level of contact between the dispersing emissions and the faces of nearby buildings.

4.4. Urban Pollution Monitoring

Pollution levels in urban areas are monitored on a continuous basis. The UK National Monitoring Network has about 100 sites of which 81 are in urban areas (AEA(1997)). There is also monitoring information from some local authority networks, such as the London Air Quality Network (SEIPH(1996)) which has an additional 33 sites in the Greater London Area. These sites usually provide data with good temporal resolution for long term trend information (for example the National Network sites produce data at 15 minute intervals) and indications of overall pollution levels in urban areas.

However, the data from the various network sites are not adequate for estimating temporal and spacial variations in urban areas over short ranges and timescales and this is of some significance for the present application. There is very little information on the variation of pollutant levels over shorter ranges, so that it is difficult to know how well network site measurements represent conditions at other places. In their recent review of the exposure to buildings to pollutants in urban areas, Hall et al(1996) looked at correlations between four monitoring sites in the Birmingham conurbation (two of which were only a few hundred metres apart) over a period of a week and found relatively low levels of correlation between the sites over this period. Despite their apparently large numbers, the spacial distribution of national and other network monitoring sites is actually quite sparse. Thus the site of a particular building could easily be 20 km or more from the nearest pollution monitoring site and in these circumstances the applicability of such monitoring data to building ventilation applications becomes uncertain.

More detailed spacial information on pollution levels is normally obtained using numerical or small scale wind tunnel dispersion modelling. Numerical models usually calculate dispersion patterns over relatively large areas with a grid resolution of 1 km or more. However, most of the standard commercial dispersion models are of limited reliability in urban areas, especially at smaller scales and shorter ranges, due to the approximations used in the modelling procedures. Small scale wind tunnel models provide excellent spacial resolution of pollutant concentrations over short ranges, especially where there is significant variation in topography (as in urban areas). This is significant for the present purposes. Most of the short range dispersion studies producing contaminant concentration patterns on buildings described later in this review are derived from wind tunnel studies.

4.5. Dispersion in Urban Areas: The effects of Time and Distance Scales

From the point of view of the exposure and ventilation of buildings, the most important feature of discharging pollutants is the concentration patterns they produce on the building surfaces. In practice, in an urban area an individual building will probably be exposed simultaneously to a large number of individual pollution sources at varying distances and heights and also timescales. The overall pollutant concentration pattern on the building will be composed of the sum of these individual contributions (dispersing plumes overlap by simple superposition).

It is the relationship between various pollution sources from these different distances and varying timescales and their proportionate combination under different circumstances which governs building contamination problems. The nature of this exposure and the relative contributions of individual sources has to be understood before the overall effect on ventilation contamination can be assessed. Hall et al (1996b) have recently reviewed this subject and described the way in which contributions from different pollution sources at different distances disperse in the atmosphere to contribute to the resultant overall exposure experienced by buildings in urban areas. A brief summary of the contents of this review is given below.

The appearance of an individual dispersing pollution source to a building downwind depends mainly upon the distance of the source, its height and the intervening topography (in urban areas this is mainly the surrounding buildings). The most important of these features is the distance of the pollution source as this governs the size, concentrations, concentration gradients and time-dependent behaviour of the plume. The effects of source distance can thus be described in terms of the characteristic distance scales, originally defined by Munn (1981), and noted below:

Microscales: These cover at from distances up to about 100m. Common examples in urban areas include pollution from vehicle exhausts, small combustion plant and standby generators, process plant discharges, nearby ventilation discharges and nuisance sources (cooking smells from kitchen extracts are commonly quoted, but there are a wide variety of other sources).

Depending upon their type local sources may be at any level from the ground to above roof level. Concentrations are usually high at short ranges and show high levels of variability both spatially and temporally, as well as being sensitive to source position, wind speed and direction. The additional effects of surrounding buildings generate quite individual concentration patterns. An important feature of exposure to local sources is the highly intermittent nature of the exposure over short time scales of the order of seconds. This affects both the process of contamination of the ventilation air and the nature of the internal exposure. This concept is especially important for odour nuisance where the nose reacts readily to very short exposure times.

Neighbourhood scales: These cover sources at distances between about 100 m and 1-2 km. At these ranges there is more vertical and lateral spreading of dispersing contaminant plumes and the very rapid variation in concentration in time and space at the shorter ranges is diminished. Dispersion patterns become more orderly (usually adopting the Gaussian distributions of conventional dispersion) but the rates of dispersion are strongly dependent on the urban layout, especially the heights, widths and occupational density of the surrounding buildings. At the scales of typical buildings (of order 10-100 m) there can remain significant gradients of concentration both laterally and vertically.

Dispersion of pollutants at neighbourhood scales has not been well researched or understood. However, recent work, including a major programme at BRE, has started to reveal its essential characteristics.

Urban scales: These cover distances between about 5 and 50 km. Pollution sources at these and greater distances disperse well above the urban canopy and spread laterally over large areas. Therefore to an individual building, there is little vertical and lateral variation of pollutant concentration and concentration gradients are not distinguishable. Also, at these distances, the heights of pollution sources become indistinguishable, except for large discharges from tall stacks.

Pollutants from sources at greater distances than these, defined by Munn as 'Regional' and 'Continental' scales, disperse and fill the whole depth of the boundary layer, to heights well above the building canopy and cover large surface areas. Thus, to an individual building they appear all-pervading, with concentration levels varying only slowly with time. Although there is no formal definition of the term, for the present purposes they constitute the 'background' concentrations to which the additional contributions of more local sources are added.

Figure 24, taken from Hall et al (1996b) shows a hypothetical example of how the contributions from sources at different distances overlay to produce an overall level of concentration at some point in an urban area. The frequency of the fluctuations increase as the pollutant source distance decreases. The high frequency component of the overall curve is due to the microscale and neighbourhood scale components. In practice, the individual components from different pollution sources contributing to the overall pollution concentration cannot be distinguished, except within limits by the use of dispersion modelling. There is only limited information on this subject as air pollution data is not usually analysed in this way. In a recent investigation of the contributions of different sources of particles to the overall levels at some PM_{10} monitoring sites, King and Bennett (1996) noted that the levels fluctuated widely and that the long range component was often a major and sometimes the dominant fraction of the total, especially during periods of exceedence of the guideline limits.

In terms of the exposure of buildings to pollutants, and especially to the siting of ventilation inlets, the most important division is thus between pollution sources at long and at short ranges. Pollution sources at long ranges appear to a building to be all pervading and concentrations are uniform over the whole structure; they also change relatively slowly with time. Thus, in terms of the ingestion of pollutants from sources at long ranges, the siting of ventilation inlets and the choice of ventilation strategy are of no significance. However, pollution sources at shorter ranges can produce large variations in concentrations across buildings, both across individual faces and between the different faces. Here the effects of inlet siting on the ingestion of pollutants and the use of specific ventilation strategies are much more significant and there are opportunities for designing ventilation systems to minimise inlet pollution levels.

In practice, the ratio of the contributions from short and long range sources can vary considerably depending upon both the weather pattern and the generation cycles of local sources. For example vehicular traffic usually shows strong cyclic patterns and there are often large differences in 'background' concentration levels between westerly winds associated with Atlantic depressions and easterly winds associated with anticyclones and the transfer of air from the continental landmass.

Figure 25 shows a qualitative diagram of the regions around a building from which pollution sources produce different types of plume interaction in a single wind direction. Firstly, there is a region around the building at some distance to the sides and rear for which there is no interaction at all. Then, further upwind is the region where pollution sources interact with the building but generate no significant concentration gradients on it. Finally, around and immediately upwind of the building there is a region where pollution sources produce significant concentration gradients on the building. It is important to note that this region extends downwind of the building and may extend a significant distance to each side.

The size and shape of these different areas will depend upon both the shape and size of the exposed building and upon the surrounding urban structures. The arrangement of the surrounding urban structures, in terms of their size, shape, occupational density and other factors, modify plume paths and their rates of dispersion. On a flat plain with only a single building, it is possible with current experimental and theoretical knowledge, to define at least approximately these different regions. However, it is currently less easy to do this for a building surrounded by the other structures in an urban area, in some cases at very high occupational densities, and the research database in this area is quite limited. There are few field measurements of the contaminant concentrations on the faces of buildings to provide quantitative data. In some recent work, Kruger (1994) measured the concentrations of CO on the opposite sides of a building, one of which was next to a busy street, for a period of about ten days. Some results of these measurements (re-analysed) are shown in Figure 26. They show the absolute concentrations, the lowest common level and the difference between the two readings. It can be seen that there was not a consistent difference between the measurements either side of the building and Kruger noted a strong dependence on wind direction.

The diagram in Figure 25 is for a single wind direction, while in practice a building will be exposed to winds from all directions. To first order, for all wind directions the inner region of interaction that produces significant concentration gradients on the building becomes a circle. However, in practice urban areas are not usually amorphous, there are alignments of buildings and streets with particular wind directions for example, so the boundary of the inner region of interaction will not normally be circular. Furthermore, as the shapes of the area defining the inner regime will also generally vary with wind direction, a simple diagram of this sort may not necessarily define the inner region of interaction very well.

Diagrams like that of Figure 25 have been produced by a number of authors in relation to wind loading of structures, Hall et al (1996a) and Cook (1985, 1990) describe some of these. However, they have not (to our knowledge) been produced to account for the effects of dispersing contaminants. One of the requirements of the research programme, of which this review is part, will be to provide this type of information on the regions around a building which produce the different types of exposure.

4.6. Pollutant Concentration Patterns on Buildings from Local Sources

4.6.1. Background

There is a substantial database of measurements of contaminant plume dispersion patterns associated with the effects of buildings. Earlier work up to about 1980 was extensively reviewed by Hosker (1980). More recent work has been investigated by Hall et al (1996a), who in the course of producing their recent review of the needs for a simple urban dispersion model, found over 400 references on the subject. However, as they also commented, the literature is of a disparate nature, containing few consistent research themes. Only a limited amount of this literature is directly concerned with the present interest, contaminant concentrations on the building itself, the majority is concerned with concentration patterns at the ground, mostly downwind of the building; previously this has been the subject of greater interest in air pollution studies. Also, of this limited subset, only a few papers deal with the impaction on buildings from upwind sources. The greater concern has been from the effects of sources on the building itself with regard to direct contamination of ventilation inlets. Until relatively recently there has been an equally limited interest in short range dispersion within the urban canopy and few papers provided concentration measurements on building surfaces within the canopy. The proceedings of the recent conference on Wind Climate in Cities (Cermak et al (1993)) also provides a useful cross section of work in this area.

Since the subject has been comprehensively reviewed by Hosker (1980) and by Hall et al (1996a), this will not be repeated in detail here. However, the most relevant results are reproduced in the next two sections of this review. Virtually all the data presented here is from small scale wind tunnel model studies.

In the same way that the airflows around and wind pressure patterns on buildings are largely independent of scale and windspeed for typical building shapes, the dispersion patterns of passive contaminants are also largely independent of scale and windspeed. The actual contaminant concentrations vary according to the formula,

$$\frac{C}{QUL^2} = const$$

where C is the contaminant concentration at some point in the dispersing plume,
Q is the discharge rate of the contaminant,
U is the windspeed and
L is the dimensional scale.

The constant is usually known as the dimensionless concentration, K, so that the concentration at some point in the flow is given by,

$$C = K.\frac{Q}{UL^2}$$

Although it is not much commented upon, it must be noted that the equation shows that windspeed is an important parameter in determining contaminant concentrations since, to first order, concentration is inversely proportional to windspeed. It is common for windpeeds within the urban canopy to be relatively low and contaminant concentrations to be relatively high as a result. Local windspeeds can be modified considerably by the detailed structure of urban areas. Recent work at BRE and UMIST has provided information on this matter, and an improved method of determining the surface roughness of urban layouts has been developed (Macdonald et al (1997)).

4.6.2. Pollutant Concentration Patterns on Single Buildings in Isolation

Some of the earliest building related measurements were of concentration patterns on buildings due to flush roof vents, by Halitsky (1963). The measurements covered a variety of building shapes, mostly not far removed from the cubical form. Some of this data is shown in Figure 27 and is typical of this sort of measurement. Concentrations are high near the vent and diminish with increasing distance from it. Most importantly, there are recorded levels of the contaminant both upwind of the vent and over all the surfaces of the building except the upwind face (which is not shown in the diagram).

Additional measurements of the same sort were collected by Wilson (1976), who in this and a series of other papers (these are discussed more fully in Hall et al (1996)) was concerned with predicting the contamination of ventilation inlets from discharges on the building itself. His measurements covered a wider range of building shapes than Halitsky, including the low, wide forms common for large industrial and commercial buildings. Some of Wilson's results are shown in Figure 28. Wilson and Winkel (1982) continued this work, looking at dispersion patterns over a wide variety of building shapes, Figure 29 shows a selection of these, with the intention of defining envelopes of limiting concentrations at different distances from roof vents. One of the figures from this work, showing the effects of stack height on the contaminant concentrations on the building, are shown in Figure 30. A large number of measurements of this sort were made and analysed to produce a design equation for contamination of vents on the building, of the form,

$$\frac{C_r}{C_{ro}} = \exp\left[-11\frac{(h_s^2 + 2h_s\Delta h)}{R^{0.5}x^{1.5}}\right]$$

where C_r is the maximum roof level concentration from an elevated stack
C_{ro} is the maximum roof level concentration from a flush stack
h_s is the stack height
Δh is the plume rise
R is a roof wake scaling parameter and
x is the distance to the ventilation inlet

The results of this and Wilson's other work on vent contamination are incorporated into the advice on siting discharge vents published in the ASHRAE handbook (ASHRAE(1995)).

The impaction of upwind contaminant plumes on isolated buildings has received little attention in generic studies. Apart from some early work by Puttock and Hunt (1979), Wilson and Netterville(1978) made a number of measurements of the impaction of a roof level upwind source on a cubical building. Figure 31 shows their published example of these measurements, for a wind direction on to the face and the corner of the cube respectively, together with a diagrammatic representation of the impaction of a plume on to the building face. This latter gives little idea of the complex behaviour that can in fact occur, which is discussed more fully by Hall et al (1996a). Wilson and Britter (1982) used this and the earlier data of Wilson and Winkel(1982) to produce some simple empirical rules for estimating the maximum likely concentration on the building surface due an impacting plume whose source may be on, above or ahead of the building. This work was again incorporated into the guidance in the ASHRAE handbook.

There have also been some measurements by Hall et al (1996) of the impaction of plumes on a relatively low, wide building from upstream sources at various heights. This work was mainly concerned with the rapid fluctuations in plume concentration that occur at short ranges, but the initial part of the work required determining the mean concentrations. Figure 32 shows concentration patterns on the building from these measurements for sources upwind at different heights and for different wind directions. The Figure shows the building surfaces 'unfolded', so that concentration patterns on all the faces can be seen.

4.6.3. Pollutant Concentration Patterns on Buildings in Urban Arrays

Until relatively recently there have been few measurements of this sort, the majority of dispersion measurements associated with buildings have been concerned with isolated structures. This position still remains, but the greater recent interest in urban areas has resulted in a small but growing literature on dispersion in urban arrays. There have always been specific studies of dispersion within urban sites, some of which are published (for example, the recent work of Bachlin et al (1991), and of Wilson and Lamb (1994)). However these are usually of a sufficiently idiosyncratic nature to prevent drawing more general conclusions, though Bachlin et al tried to do so in their own study. This work has to some extent been covered in Hall et al's (1996a, b) reviews, but some additional information is provided here.

Some early systematic measurements of dispersion within urban arrays were made by Wedding et al (1977), who used a fairly close packed regular rectangular array of building blocks, with an area occupational density of about 50% representing a typical US city layout. The contaminant sources were pairs of line arrays in the streets (representing vehicle discharges). This early work showed some of the typical characteristics of short range dispersion in closely packed building arrays. There were large and often quite complex variations in contaminant concentration patterns on the faces of the buildings, with high contaminant concentrations at some points. Also there were marked changes in concentration patterns with varying wind direction over the array, significant effects due to modifying the building shapes (especially varying the heights) and both positive and negative vertical gradients of concentration on different building faces. Some examples of this work (taken from Cermak et al (1974), which provides a different subset of the same data to that of Wedding et al) are shown in Figure 33. These diagrams show concentration contours on the building faces for one of the test conditions in two wind directions and with one building modified by an additional block on its upper surface. The variations in concentration patterns on the building surfaces are clearly apparent.

There has been a much greater interest in this type of dispersion in more recent years, together with more serious attempts at developing appropriate numerical models. A major interest has been the dispersion of contaminants in 'street canyons'. Though there is no formal definition of this, it has tended to imply particularly deep wells in narrow streets between tall buildings. However, in practice urban areas can have large variations in the building occupational density, between 5% and 90%, with attendant variations in the dispersion patterns and effects due to surrounding buildings. There are three main sets of dispersion data of this type, described briefly below.

The first is that of Dabbert and Hoydish (1991) and Hoydish and Dabbert (1994), who investigated the dispersion of line sources at the ground within block arrays of about 65% occupational density (equivalent to a city centre density of buildings), in which they measured both concentration patterns at the ground and on the faces of the buildings. Figure 34 shows the building layout and some of the results of the earlier paper, which show concentration patterns on the building faces on the up and downwind sides of the street and the contributions to the overall concentration due to sources in streets and avenues. Two important features of the measurements are the marked variations in contaminant concentration over the building faces and the marked differences in concentration on building faces on the upwind and downwind sides of the same street.

The second is the work from the University of Hamburg Meteorological Institute over the last few years, which has produced a number of fundamental studies of dispersion within the urban canopy (Meroney et al (1995,1996), Pavageau (1996a,b), Rafailidis (1995a,b)). Most of this work is concerned with dispersion within two-dimensional rows of streets. Figure 35 shows examples of this work. The upper diagram is of concentration contours in a cross section of a narrow street with the wind blowing from left to right. The lower diagram shows concentration contours on the upwind and downwind faces of the buildings. As with Dabbert and Hoydish (1991) measurements, the contours show higher concentrations on the upwind building face (by about a factor of two) then on the downwind face. These studies also remark on a number of other characteristics of dispersion in narrow spaces between buildings. These are the high levels of contaminant concentrations that can occur, the effects of the upwind urban building array on local dispersion patterns and the large variations in concentration that can occur over a single building face.

The third data set is that which is currently being collected at BRE as part of a long running programme aimed at developing a numerical urban dispersion model. Some initial studies for this have been reported by Hall et al (1996d). There have also been related field experiments by MacDonald (1997) and some earlier work of a similar sort by Davidson (1996). The experiments are intended to provide information on both dispersion and wind speeds over urban building arrays. The importance of windspeed in altering contaminant concentration levels has been noted previously. The types of urban arrays used in the experiments are shown in Figure 36. They cover a wide range of building occupational densities (from 5% to 92%) and of building shapes from cubical to wide rows and square arrays of buildings. Some of the results of this work have already been discussed in Hall et al's reviews, and will not be detailed again here. The experimental programme was initially concerned with defining the dispersion characteristics of urban arrays from ranges of about 1 km downwards, where dispersion patterns are affected by the shape and layout of the urban structures as well as by the overall surface roughness. It thus provides a link between conventional modelling practice, which uses only the overall surface roughness of the urban area, and the more detailed shorter range studies, some of which have been described here. The general conclusions from the work so far are:

- Rates of dispersion were largely dominated by the mean heights and widths of the buildings, other parameters such as the occupational density of the buildings, variations in height between buildings and other parameters having relatively smaller effects.

- Beyond ranges equivalent to about two rows of buildings, concentrations in the dispersing contaminant plume showed the usual gaussian form.

- At shorter ranges, within the first two rows of buildings, dispersion patterns were more complex, departing from the gaussian form and showing large variations in concentration over short distances of the type shown in the other short range dispersion measurements described in this review.

- Windspeeds were most affected by the occupational density of the buildings, their frontal areas and variability in building height.

Further work planned in this experimental programme includes investigation of the complex contaminant patterns around buildings from nearby sources in urban arrays and of dispersing contaminants from elevated sources. The other work described here is almost solely concerned with the effects of nearby, ground-based sources intended to represent local vehicle emissions.

One feature of short range contaminant patterns that is of practical interest is differences in contaminant concentrations between the roof and the walls of a building. It is commonly supposed that concentrations on a roof are invariably lower and there is a general preference for mechanical ventilation inlets to be set high up. The experimental data on this subject is in fact limited. It is common, but not universal, for concentrations from ground sources to fall with height above the ground. Dabbert and Hoydysh (1991) measurements show reducing concentration with height, as do some others. However, the BRE measurements also show cases with increasing concentration with height above the ground as the complex flow patterns in urban building layouts can generate these conditions as well. One example of a contour plot of concentrations of nitrogen oxides in a city street from a LIDAR scan, shown in the first QUARG(1993) report (also in Hall et al's (1996b) review) is reproduced in Figure 37. It shows high concentrations above roof level. In addition, contaminant sources above roof level tend to generate higher concentrations at roof level than on the ground over short ranges.

4.6.4. Vehicle-Induced Dispersion

Vehicle emissions, identified as the major local pollution source in urban areas, are associated with their own self-generated disturbances due both to the emitted exhaust heat and their own motion. The exhaust heat generates buoyancy in the discharged contaminants, which can be significant at low windspeeds. However, the dominant effect is usually disturbances generated by the moving vehicles themselves, which can produce rapid initial mixing of the exhaust material. At the low windspeeds for which pollution levels tend to be high, the relatively high speed of traffic results in a high degree of enhanced atmospheric mixing in comparison with a static vehicle of the same size. This applies especially to commercial vehicles with low levels of streamlining and these are also the larger vehicles in the traffic stream.

There has been an intermittent interest in this problem. Some early measurements of exhaust dispersion behind large diesel vehicles was carried out by Hall et al (1973), which showed both the high rates of dispersion that could occur and the importance of exhaust position to the dispersion pattern. The importance of this initial enhanced mixing of exhaust gases was recognised in early dispersion modelling studies of highway pollution and some traffic based pollution models take account of it, for example Eskridge et al (1991).

The importance of vehicle generated mixing to the exposure of buildings in urban areas is in the rapid initial mixing of pollutants discharged at street level, where windspeeds might otherwise be low. This tends both to increase initial rates of dispersion of vehicle emissions and to reduce the short range variability in concentration that is a characteristic of dispersion at microscales. Thus the concentration patterns in street canyons described in the preceding sections could be readily affected by vehicle-induced dispersion.

4.6.5. Numerical Models of Short Range Dispersion in Urban Areas

Most of the data on dispersing contaminant patterns around buildings has been derived from small scale wind tunnel experiments; however, there have also been a number of investigations using different types of numerical models. There have been two broad areas of interest, firstly that of directly computing flow patterns in street canyons and closely packed building arrays using CFD, secondly of producing a more generally useful approximate model for estimating dispersion in street canyons. Conventional dispersion models treat the urban building array only in an overall sense as a rough surface and cannot predict these details.

This subject is too complex for detailed discussion here, but there have been two useful recent reviews of the problems involved. Berkowicz (1996), has discussed the requirements of this type of modelling for estimating traffic pollution and considered both CFD and empirical models. His conclusions were that some of the present empirical models are useful for predicting contaminant patterns in a broad sense, but are of limited accuracy and cannot predict detailed contaminant patterns. Berkowicz also remarks that 'even the more sophisticated numerical models based eg on the k-e approach will have difficulties in handling the complicated boundary conditions, although they can be useful for some specialised applications'. The other review is by Hanjalic, Obi and Hadzic (1997), who were concerned with modelling flows through arrays of wall-mounted cubical obstacles, a very similar case to flows through urban areas. They considered a variety of CFD numerical modelling techniques, but came to similar conclusions to Berkowicz, that there remained many deficiencies in this type of model. In particular, they remarked that though the models can often generate acceptable mean flow characteristics they were significantly less good at estimating turbulence characteristics. This is especially important in estimating the dispersion of contaminants, which is directly driven by the flow turbulence. They further remarked on the need for time-dependent calculations of flows with unsteadiness, which is the normal case for the short range flows in urban canyons, without which results are unreliable.

4.7. Discussion of Urban Pollution and Dispersion

It will be appreciated from this brief review that a number of features of urban pollution and the dispersion of contaminants affect the exposure of buildings to contaminants. In considering the position of ventilation inlets and the development of natural ventilation strategies, it is the variation of contaminant concentration around the structure and some consistency in this variation that makes this choice a useful design principle. This, in turn depends on the relative contributions to the overall contaminant level of 'local' and 'distant' sources (as it is only the former that generate significant variations in contaminant concentration over the building). To predict this requires a knowledge of the area around the site, as in Figure 3, for which contaminant sources can be considered to be 'local' and the nature of the contaminant concentrations patterns over the building that they generate.

At present none of these parameters is sufficiently well studied to allow a set of empirical ground rules to be laid down for this type of ventilation design. The relative contributions of 'local' and 'distant' pollution sources to overall levels is uncertain and the spacial variations in pollution level in urban areas (as distinct from the temporal variation at monitoring sites) is not well studied, especially over short distances. Figure 24, which defines the ranges of different types of source is qualitative due to lack of data. The work on short range dispersion within close packed building arrays and 'canyon' streets, described in the previous sections of this review, has established many of the important features of this type of contaminant dispersion. However, there are only a few of these studies and they cover a limited range of the governing parameters. Most are concerned with contaminant sources in the immediate locality of the building (in the same or adjacent street in which contaminant concentrations were recorded) and only with sources at the ground.

One of the important features of these short range dispersion patterns within the urban canopy is their high level of spacial and temporal variability. A consequence of this is that it may only be possible to deal with contaminant concentration patterns in a probabilistic sense, that is, of the probability of one of a number of possible patterns occurring.

5. DISCUSSION

The different parts of this review have mostly been discussed in detail locally; this section presents an overall summary of the review. In the introduction it was noted that the essential features in predicting the internal levels of external contaminants in buildings were,

- The nature of local pollution sources in urban areas, their proportionate contribution to the overall pollution level around a building and the dispersion patterns they produce on the building surfaces in urban areas.
- The pressure distributions generated on building surfaces on urban areas.
- The regions of concurrence of both high pollutant concentration and high surface pressures on building surfaces, which lead to the ingress of pollutants.
- An understanding of the relationship between indoor and outdoor pollution levels, which requires field measurements.

To deal with these matters in combination requires a multidisciplinary approach. As was also noted in the introduction, there is little overlap between these disciplines, so that there are effectively no publications specifically aimed at the present application.

This review has shown that most of the items noted above have been investigated at least to the level where the broad character of what can be expected is known. However, there is a general lack of more detailed information sufficient for generating reliable guidance on ventilation design in urban areas.

The nature of urban pollution sources are quite well known, although their dispersion patterns over scales below a kilometre in urban areas are not so well understood and it is often difficult to define local pollution sources with any precision. Also, although there is good long term temporal data on pollution levels in urban areas (where most measurements are made), information on short term variations (below about ten minutes) and on spacial variations, especially within kilometre scales, is sparse. It can thus be difficult to apply normal monitoring data to specific urban sites except in a broad-based way.

The principals of natural ventilation are quite thoroughly known, but require pressure differences on the building envelope. These are relatively well understood for isolated structures but distinctly less well quantified in urban building arrays. The surface patterns on buildings from locally dispersing contaminants have received only limited attention, less than with building surface pressures, both for isolated structures and those within the urban array. There is no experimental data with common pressure and dispersion information, which is vital for estimating the ingress of contaminants, and without which it is difficult to correlate the separate dispersion and wind pressure data from the two disciplines.

The range from which pollutant sources can generate significant variations in concentration patterns over buildings (Figure 3), and for which the choice of ventilator position becomes significant, is also presently an unknown. This is important to the production of adequate guidance as it both defines the region of immediate concern for the designer and indicates the range beyond which all contaminant sources can be considered as 'background' pollutants. This, in turn affects the relative balance between these two components of the overall urban pollution level. The data on pressure on buildings in urban arrays indicates that the detailed effects of pressure patterns on buildings fade quite rapidly beyond the nearest two rows of buildings.

The greatest information deficiency is probably in the area of field measurements of internal/external contaminant levels. There have been only a few studies, all for short periods typically of the order of ten days (the longest, by Rubino et al (1995), is for 60 days). This is inadequate to permit an understanding of the variation in contaminant ingress with the weather and pollution patterns, both of whose characteristic cycle times is one year.

The two most important information deficiencies of those outlined above are the subject of investigation in the research programme of which this review is part. These are:

- Field measurements of internal/external pollution levels in a polluted urban area and their variation with the local pollution and weather patterns, over long time scales.

- The variation of pressure and concentration patterns on buildings in urban arrays, collected on identical urban layouts in the same experiments. This will allow both determination of the critical region of interest (as in Figure 3) and the regions on the building surface where both surface pressures and contaminant concentrations are high. It will also provide a link between other dispersion and wind pressure data.

6. CONCLUSIONS

1. Information on the ingestion of pollutants into buildings and the ways in which this may be minimised is needed for effective design for natural ventilation in urban areas. There is currently no formal guidance of this sort and to date only a few tentative and, to some extent, conflicting strategies have been offered.

2. There are few measurements of the relative levels of internal/external pollution levels. These show varying degrees of attenuation (sometimes negative) internally of the external level. Periods of measurement are too short (typically 10-20 days) to reveal the longer term variation over a minimum of one year which is the characteristic cycle time for the weather, air pollution and ventilation patterns.

3. External urban air pollution is monitored as a matter of course and pollution sources are subject to high levels of regulation. There is regular monitoring of urban pollution levels and the data is readily available. However, monitoring sites are relatively sparsely distributed and mainly provide good temporal data for regulatory purposes. There is little information on either the spacial variation (needed to apply existing data to specific sites) or to the short term variations in concentration (at time scales below an hour) which affect the ingestion of pollutants into buildings.

4. The ingestion of pollutants into buildings occurs at the points of confluence of both high pressure and high contaminant concentration. In urban areas this is affected by the urban array of buildings around a given site. There is only limited data on contaminant dispersion and building pressure distributions in urban arrays, though sufficient to provide their general characteristics under of these conditions. However, it does not provide systematic data over the range of urban building layouts and the dispersion and pressure data, coming from different specialisms, do not provide readily comparable experiments. There is no single experiment providing data on both pressure and contaminant concentration distributions on buildings. It is thus difficult to use the existing, limited, database to generate suitable guidance.

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APPENDIX A

EXPOSURE LIMITS AND GUIDELINES FOR THE MAJOR AIR POLLUTANTS TAKEN FROM AEA (1997).

DETR Limits, EPAQS Recommended Standards, EC Directives, WHO and UNECE Guidelines for CO, NO_2, SO_2, O_3, PM_{10}, Lead, Benzene and 1,3-Butadiene.

a) Carbon Monoxide

Guideline set by	Description	Criteria Based On	Guideline Value ppm (μgm-3)
Department of the Environment	-	-	-
Expert Panel on Air Quality Standards	Health Guideline	Running 8-hour mean	10 (11.6)
European Community	-	-	-
World Health Organisation	Health Guideline Health Guideline Health Guideline Health Guideline	15-minute mean 30-minute mean 1-hour mean 8-hour mean	87 (100) 50 (60) 25 (30) 10 (10)
United Nation Economic Commission for Europe	-	-	-

b) Nitrogen Dioxide

Guideline set by	Description	Criteria	Guideline Value ppb (μgm-3)
Department of the Environment, Transport and the Regions	V GOOD Air Quality GOOD Air Quality POOR Air Quality V POOR Air Quality	Peak hourly average concentration in a 24-hour period	< 50 (96) 50 - 99 (96 - 190) 100 - 299 (191 - 572) >=300 (573)
Expert Panel on Air Quality Standards	Acute effects	1-hour mean	150ppb
European Community	Limit Value Guide Value Guide Value	Calendar year of data; 98%ile of hourly means. 98%ile of hourly means. 50%ile of hourly means.	104.6 (200) 70.6 (135) 26.2 (50)
World Health Organisation	Health Guideline Health Guideline Vegetation Guideline Vegetation Guideline	1-hour mean Daily mean Running 4-hour mean Annual mean	210 (400) 80 (150) 50 (95) 16 (30)
United Nation Economic Commission for Europe	Vegetation Guideline	Annual mean	15 (29)

c) Sulphur Dioxide

Guideline set by	Description	Criteria	Guideline Value ppb (μgm-3)
Department of the Environment	V GOOD Air Quality GOOD Air Quality POOR Air Quality V POOR Air Quality	Peak hourly average concentration in a 24-hour period.	<60 (160) 60 - 124 (160 - 332) 125 - 399 (333 - 1063) >=400 (1064)
Expert Panel on Air Quality Standards	Health Guideline	15-minute mean	100 (266)
European Community	Limit Value	Pollution Year (median of daily values)	30 (80) if smoke (1) > 34 45 (120) if smoke <= 34
	Limit Value	Winter (median of daily values October - March)	49 (130) if smoke > 51 68 (180) if smoke <=51
	Limit Value (2)	Pollution Year (98%ile of daily values)	94 (250) if smoke > 128 131 (350) if smoke <=128
	Guide Value	Pollution Year (mean daily values)	15 - 23 (40 - 60)
	Guide Value	24 Hours (daily mean value)	38 - 56 (100 - 150)
World Health Organisation	Health Guideline Health Guideline Vegetation Guideline Vegetation Guideline	10-minute mean 1-hour mean Daily mean Annual mean	175 (500) 122 (350) 38 (100) 10.4 (30)
United Nation Economic Commission for Europe	Vegetation Guideline Vegetation Guideline	Daily mean Annual mean	26 (70) 7.5 (20)

(1) Limits for black smoke are given in 1gm (-3) for the BSI method as used in the UK.
The limits stated in the EC Directive relate to the OECD method, where OECD = BSI/ 0.85
(2) Member states must take all appropriate steps to ensure that three consecutive days do not exceed this limit value.

d) Ozone

Guideline set by	Description	Criteria Based On	Guideline Value ppb (μgm-3)
Department of the Environment	V GOOD Air Quality GOOD Air Quality POOR Air Quality V POOR Air Quality	Peak hourly average concentration in a 24-hour period.	<50 (100) 50 - 89 (100 - 179) 90 - 179 (180 - 359) >=180 (360)
Expert Panel on Air Quality Standards	Health Guideline	Running 8-hour mean	50 (100)
European Community	Population Information Threshold	1-hour mean	90 (180)
	Population Warning Value	1-hour mean	180 (360)
	Health Protection Threshold	Fixed 8-hour means (hours 1-8, 9-16,17-0, 13-20)	55 (110)
	Vegetation Protection Threshold	1-hour mean	100 (200)
	Vegetation Protection Threshold	24-hour mean	32 (65)
World Health Organisation	Health Guideline Health Guideline Vegetation Guideline Vegetation Guideline Vegetation Guideline	1-hour mean Running 8-hour mean 1-hour mean Daily mean Growing season (3) mean	76 - 100 (150 - 200) 50 - 60 (100 - 120) 100 (200) 33 (65) 30 (60)
United Nation Economic Commission for Europe	Vegetation Guideline Vegetation Guideline Vegetation Guideline	Growing season (3) mean 1-hour mean Running 8-hour mean	25 (50) 75 (150) 30 (60)

(3) Growing season is defined as April to September for WH0 guidelines, but is DAYTIME (0900 - 1500) April to September for UNECE guidelines.

e) PM_{10} Particulate Matter

Guideline set by	Description	Criteria	Guideline Value ppb (μgm-3)
Department of the Environment	-	-	-
Expert Panel on Air Quality Standards	Health Guideline	Running 24-hour mean	50
European Community	-	-	-
World Health Organisation	Health Guideline*	24-hour mean	70 (If SO_2>=125 (48ppb))
United Nation Economic Commission for Europe	-	-	-

* Thoracic Particles

f) Lead

Guideline set by	Description	Criteria Based On	Guideline Value ppb (μgm-3)
Department of the Environment	-	-	-
Expert Panel on Air Quality Standards	-	-	-
European Community	Limit Value	Annual Average	2
World Health Organisation	Health Guideline	Annual Average	0.5 -1
United Nation Economic Commission for Europe	-	-	-

g) Benzene

Guideline set by	Description	Criteria Based On	Guideline Value ppb (μgm-3)
Department of the Environment	Low Medium High Very High	Running 24-hour mean	< 4.5 4.5 - 9.99 10 - 29.99 >=30
Expert Panel on Air Quality Standards	Health Guideline Target Value	Running annual mean Running annual mean	5 1
European Community	-	-	-
World Health Organisation	-	-	-
United Nation Economic Commission for Europe	-	-	-

h) 1,3 - Butadiene

Guideline set by	Description	Criteria Based On	Guideline Value ppb (μgm-3)
Department of the Environment	Low Medium High Very High	Running 24-hour mean	< 0.9 0.9 - 1.99 2 - 5.99 >=6
Expert Panel on Air Quality Standards	Health Guideline	Running annual mean	1
European Community	-	-	-
World Health Organisation	-	-	-
United Nation Economic Commission for Europe	-	-	-

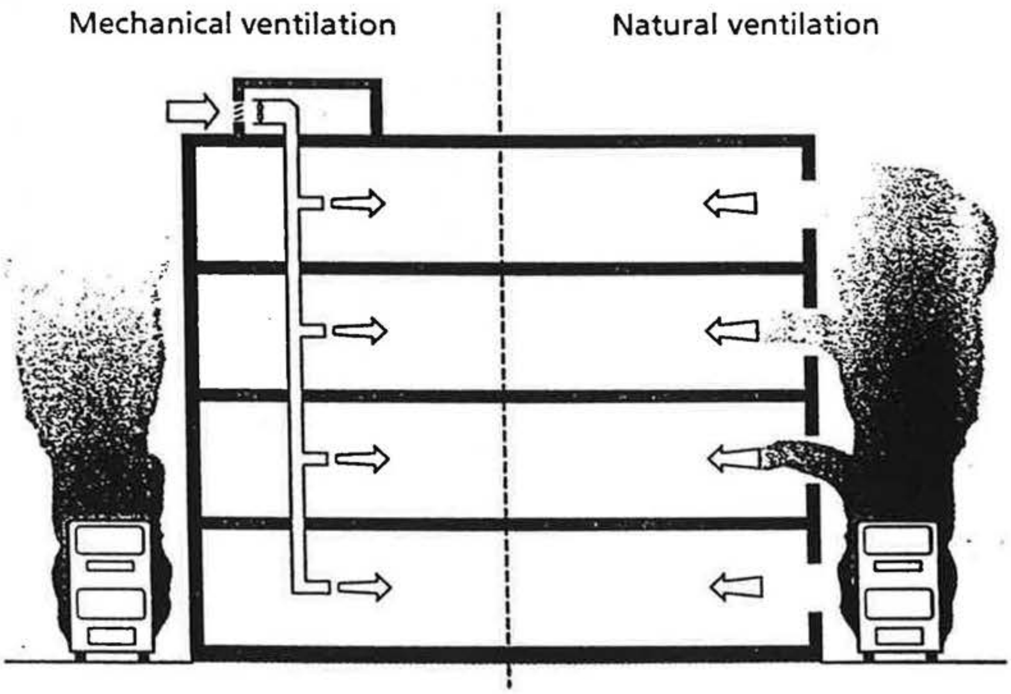


Figure 1. **Diagram of the Presently Presumed Differences Between Natural and Forced Ventilation in Polluted Urban Areas.**
From CIBSE Applications Manual AM10 (CIBSE (1997).

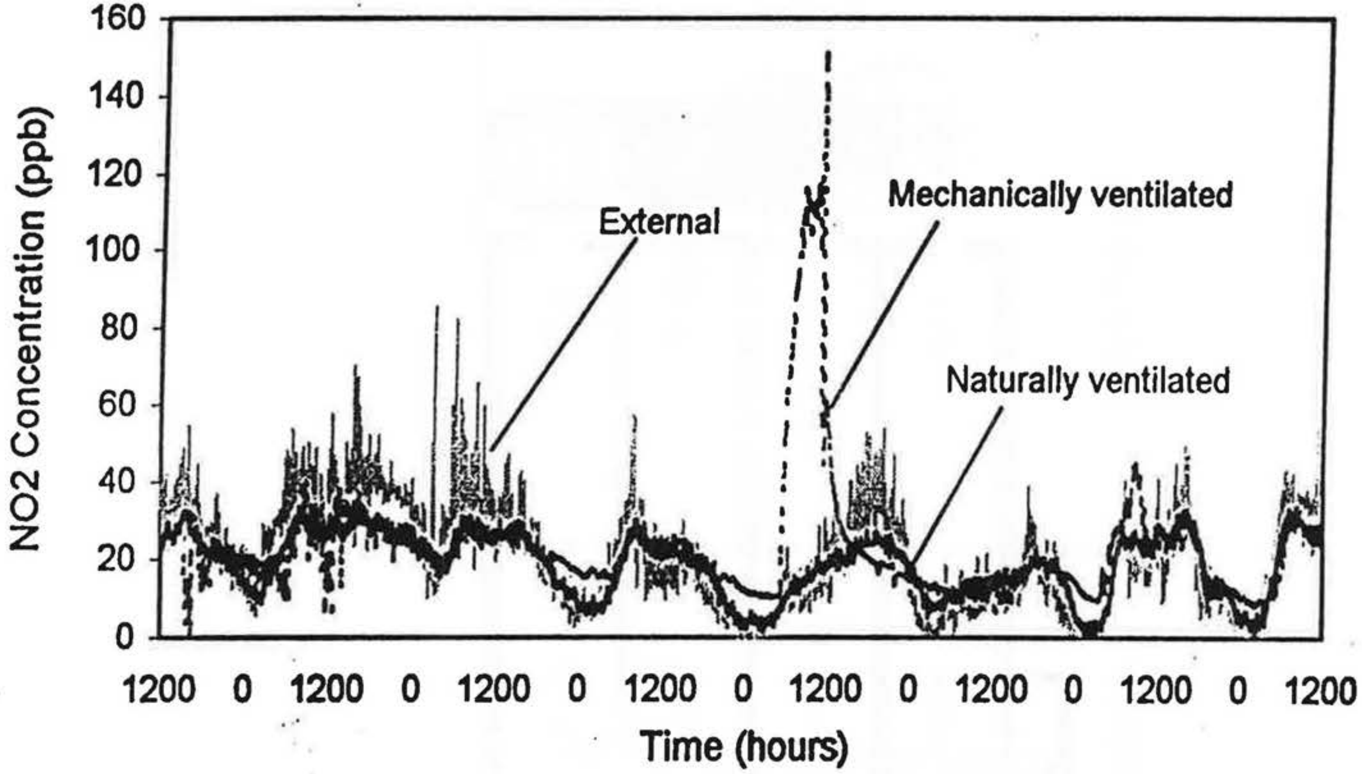


Figure 2. **Nitrogen Dioxide Concentrations (in ppb) in Two Buildings in Birmingham.**
From Kukadia et al (1996).

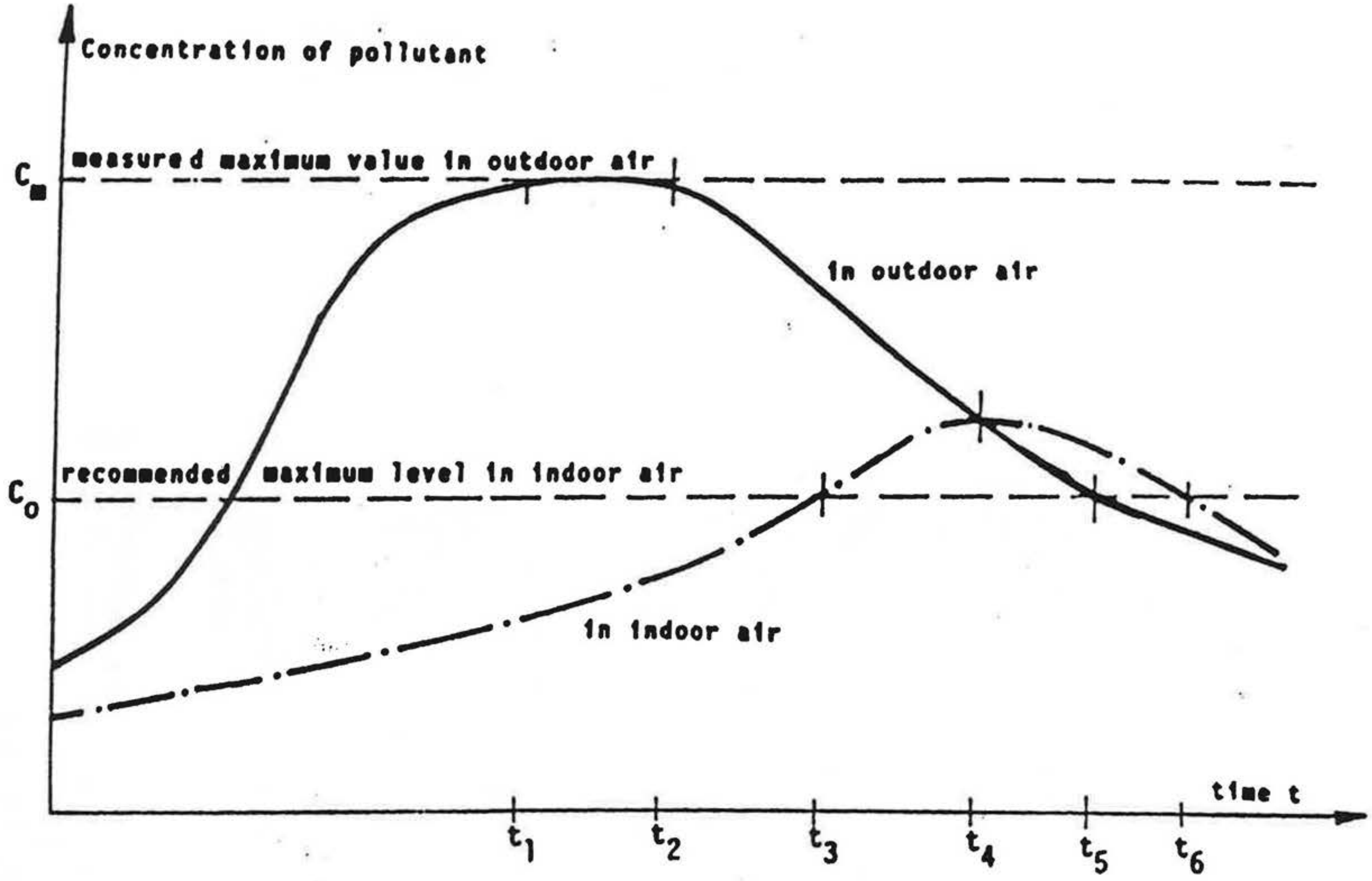


Figure 3. **Typical Response of the Indoor Environment to Transient Outdoor Pollution.**
From Trepte (1988).

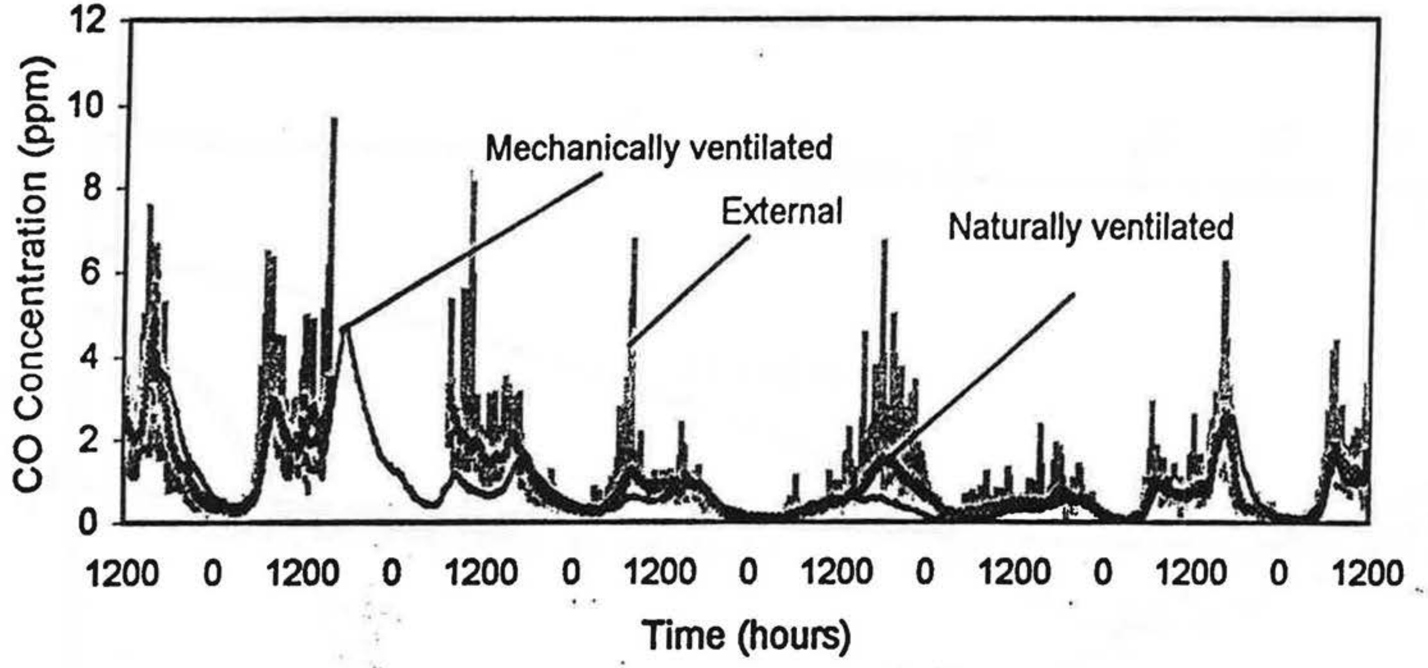


Figure 4. **Carbon Monoxide Concentrations, ppm in Two Buildings in Birmingham. From Kukadia et al (1996).**

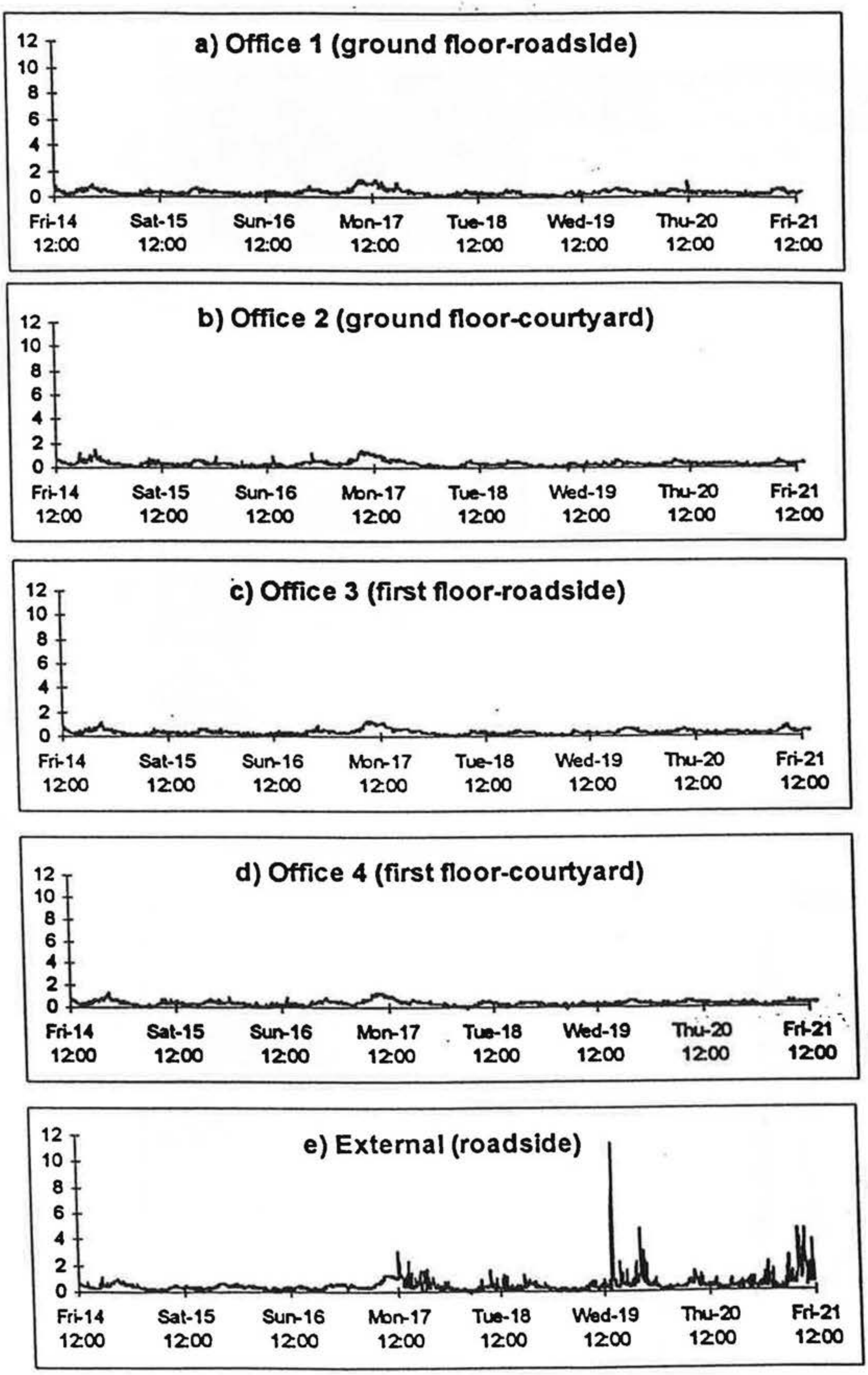


Figure 5. Carbon Monoxide Concentrations, ppm in a Building in London with its Air Intake from the Courtyard side away from the Busy Road. From Kukadia et al (1997).

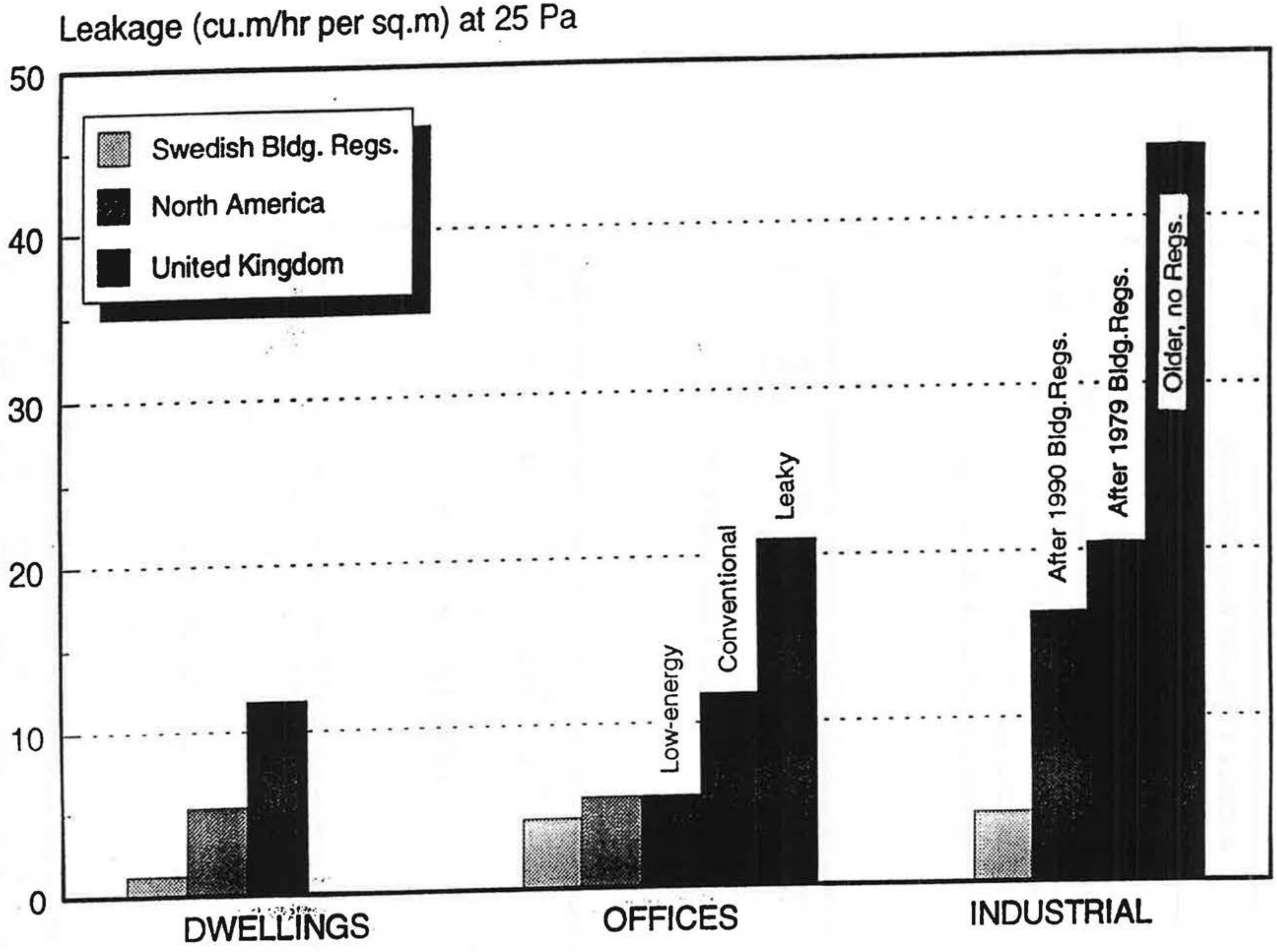


Figure 6. **Airtightness in Buildings in Various Countries. From Perera and Parkins (1992).**

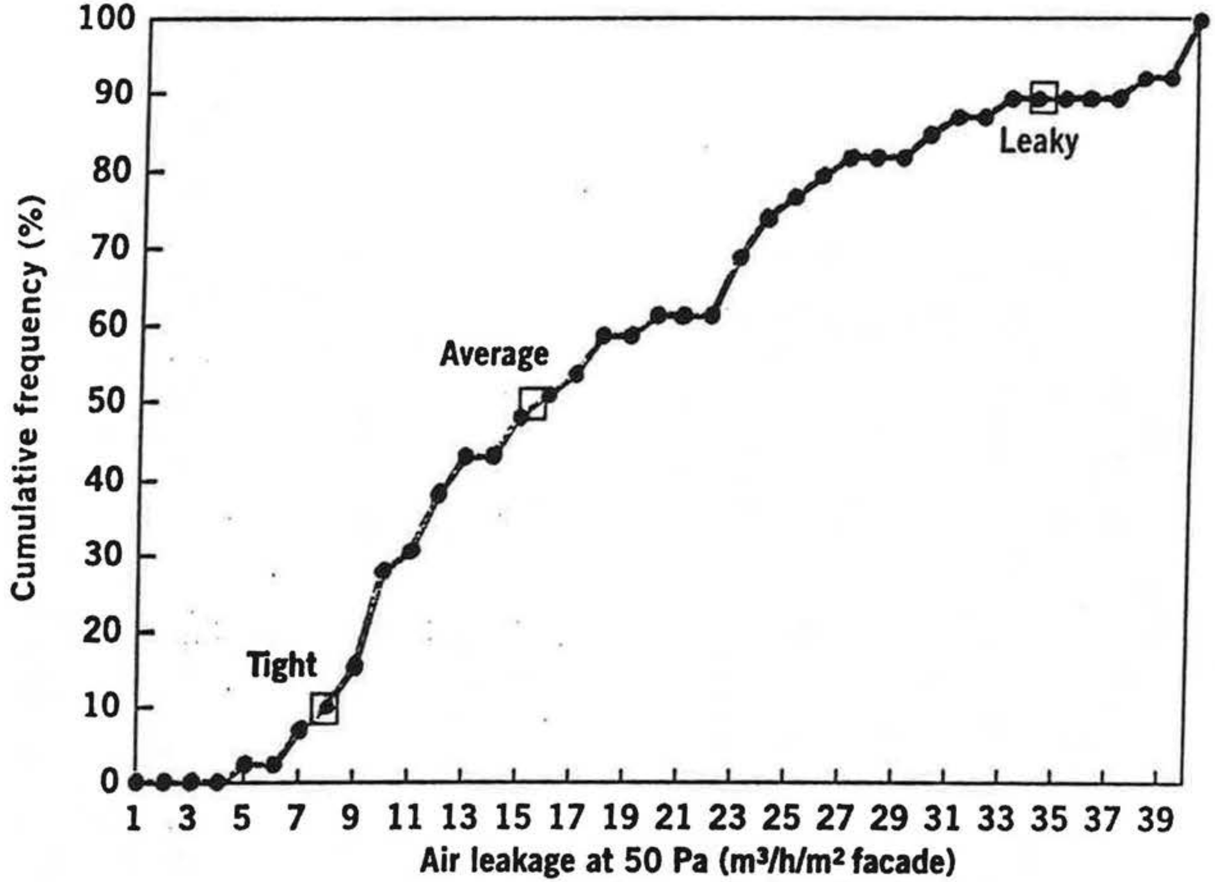


Figure 7. **The True Extent of the Air Leakage Problem. Compiled from the BRE and BSRIA Pressure testing Data.**
From Building Services Journal (1997).

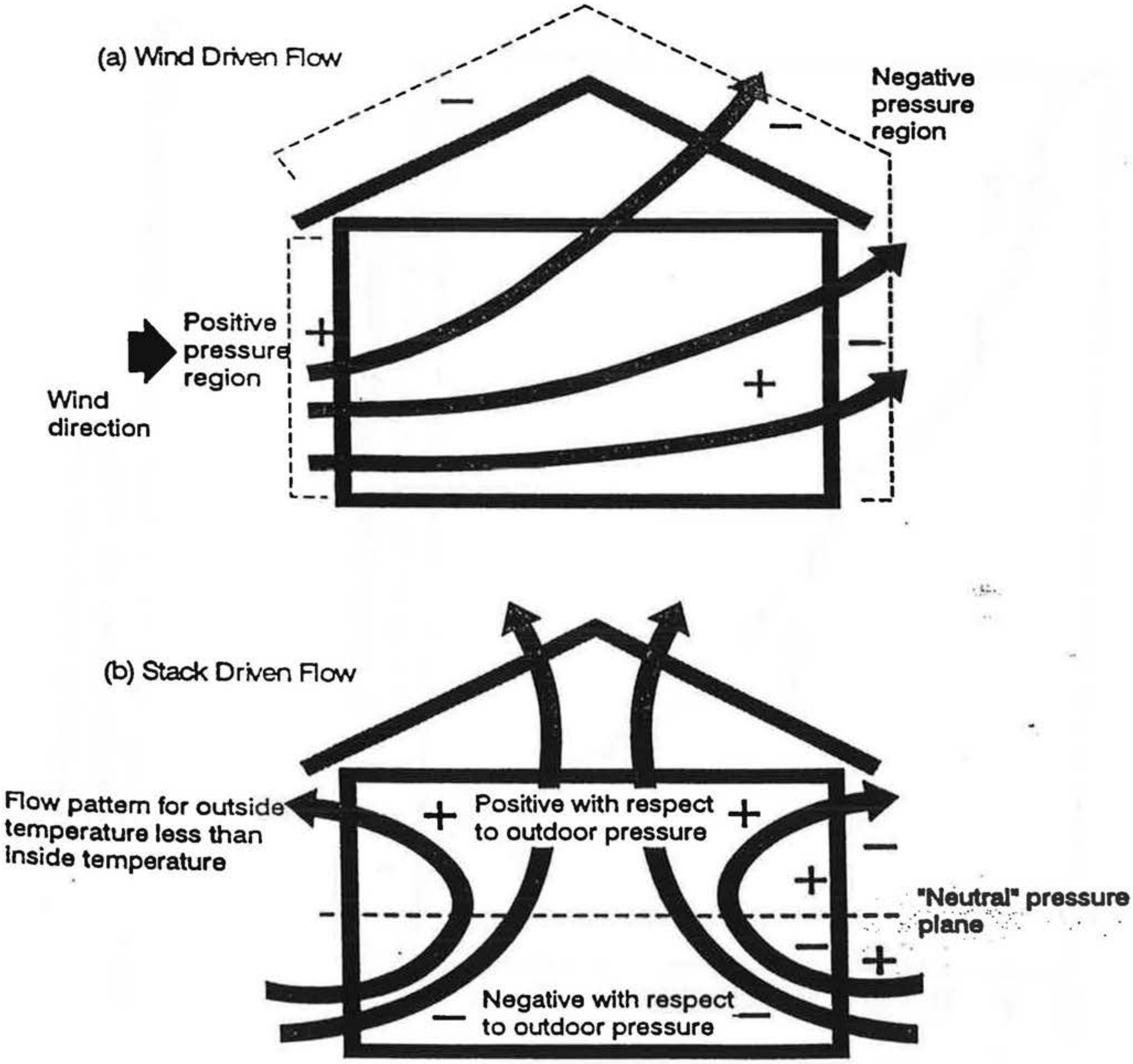


Figure 8. **Diagram of the Two Types of Natural Ventilation Airflows, Due to Wind Driven and Stack Driven Ventilation Respectively.**
(From Liddament (1996).

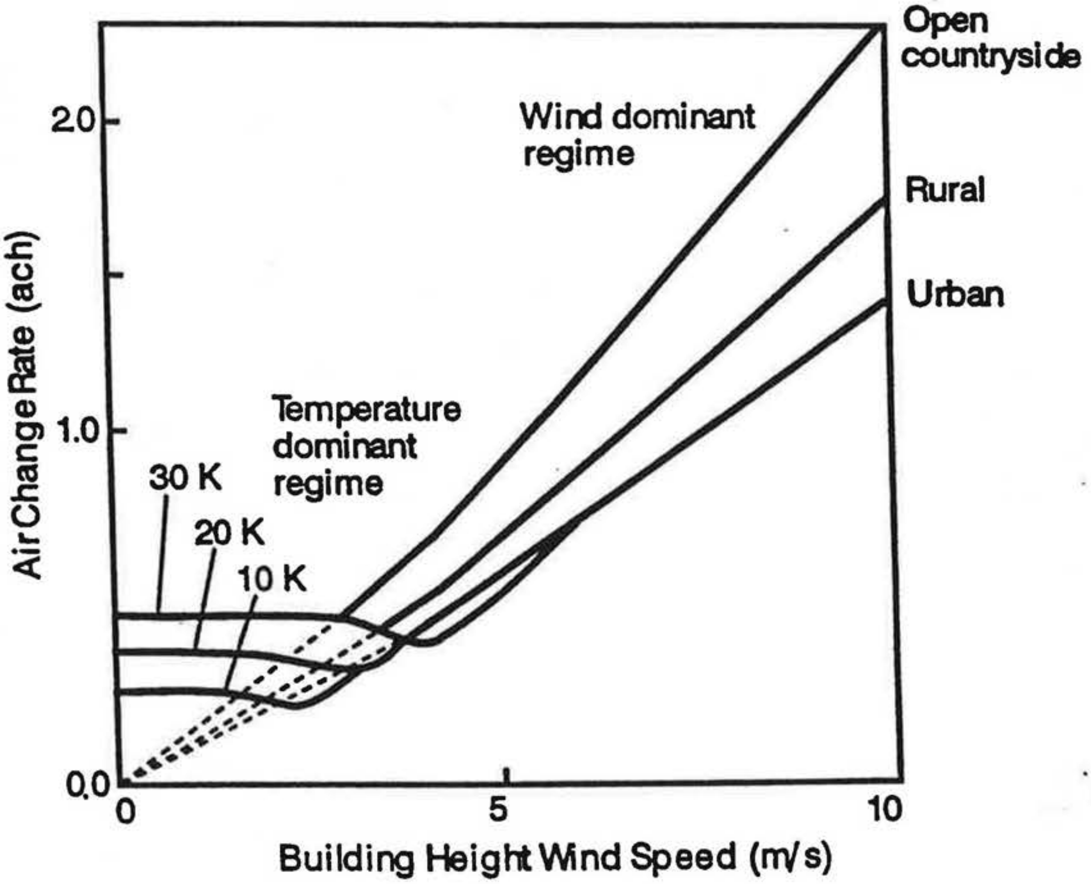


Figure 9. **Impact of Wind Speed and Temperature Difference on Natural Ventilation.**
From Liddament (1996).

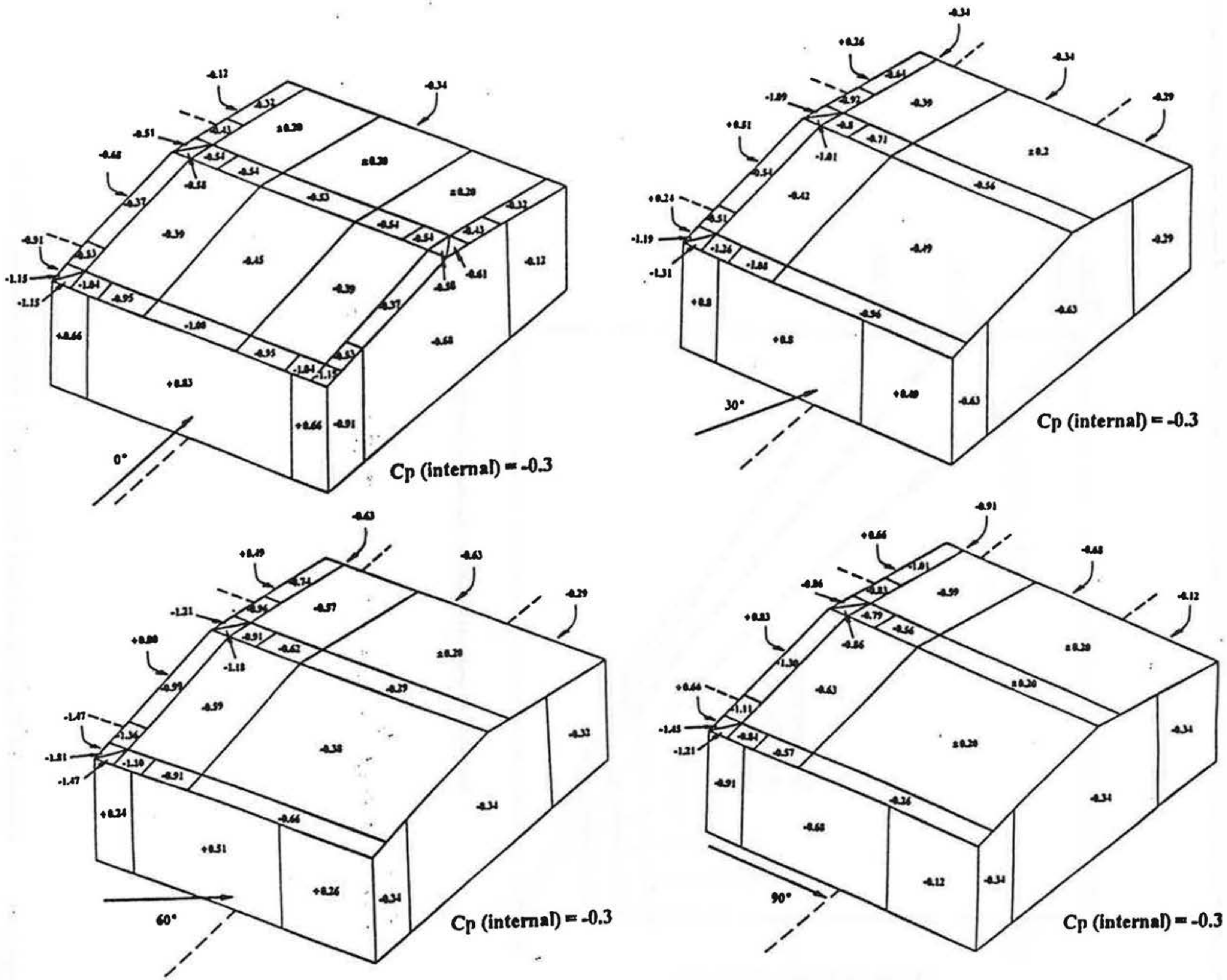


Figure 10. **Pressure Coefficients Over a Building. Derived from BRE Digest 346. From Hall et el (1995).**

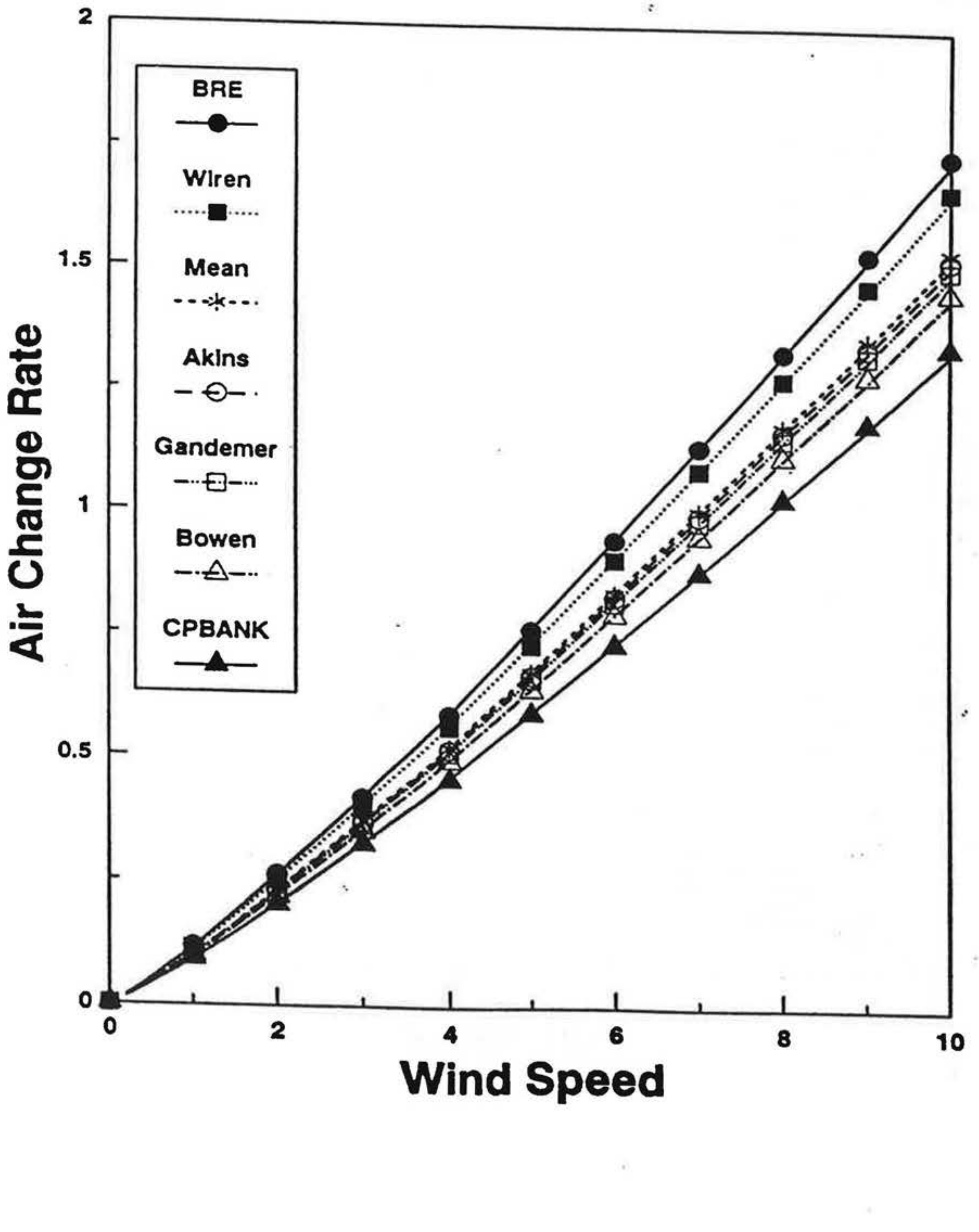


Figure 11. **Variation in Air Change Rate with Wind Speed for Buildings of L/W ratio Between 1:1 and 2:1,) No Surrounding Buildings. From Piggins (1991).**

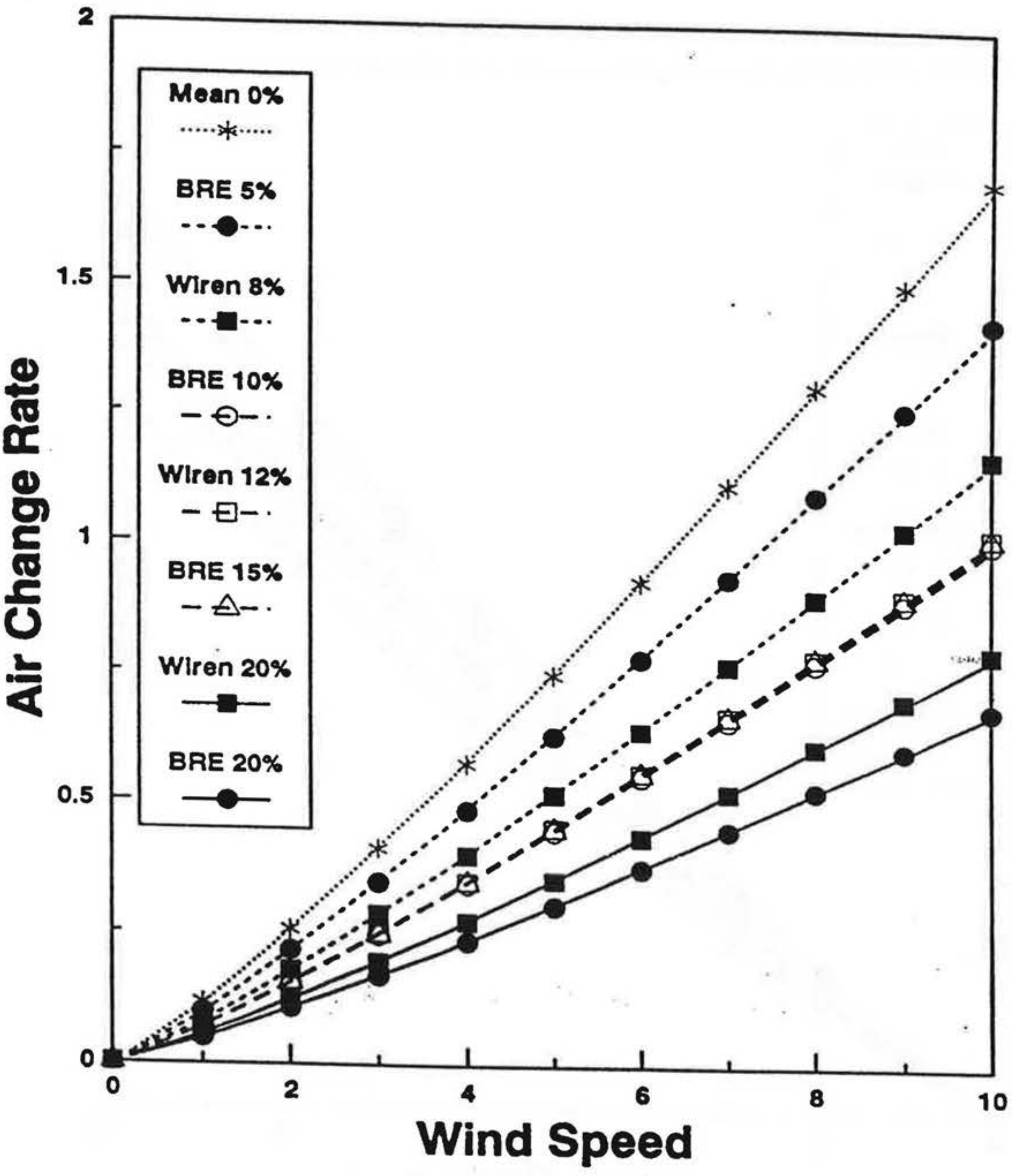


Figure 12. **Variation in Air Change Rate with Wind Speed for Different Surrounding Building Densities. BRE and Wiren Data, From Piggins (1991).**

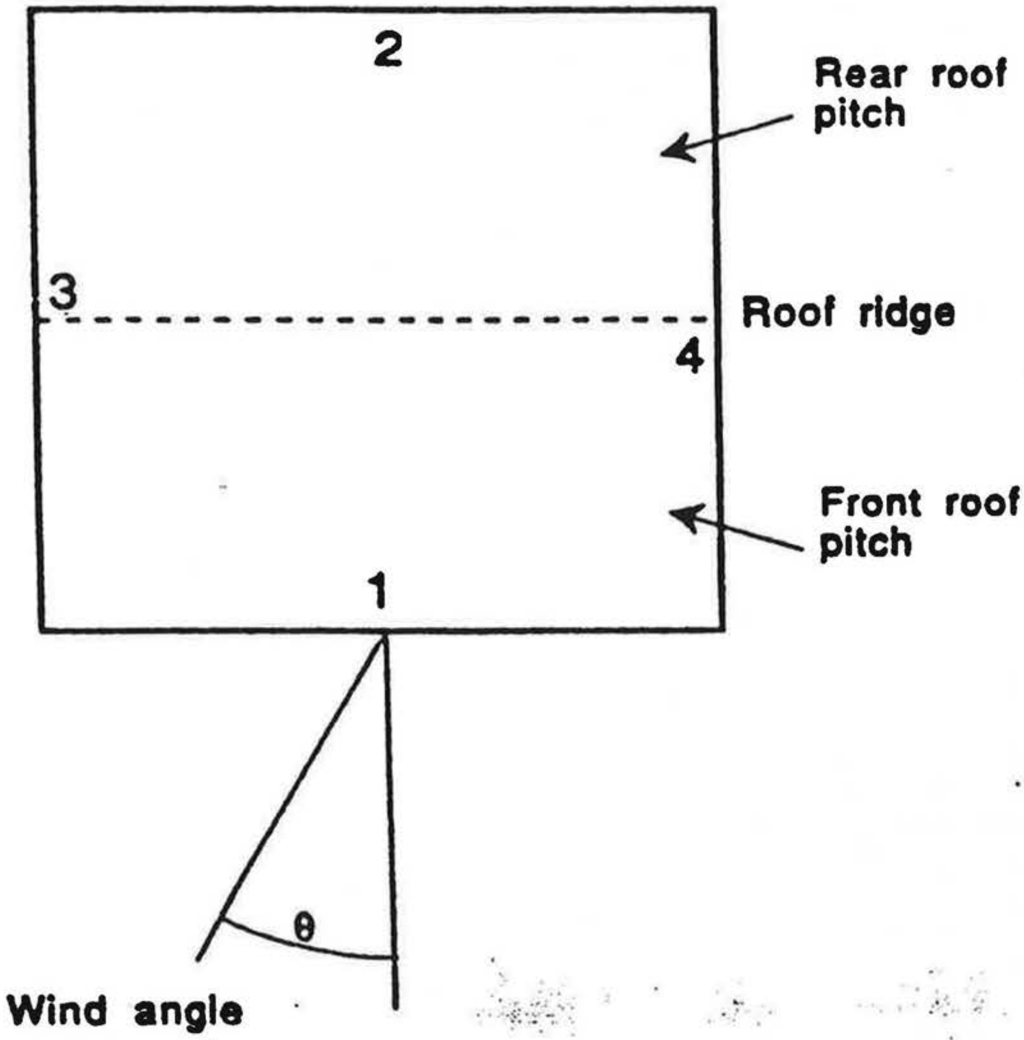


Figure 13. Numbering Convention for Figures from Wiren's(1985) Data in Tables 2, 3 and 4.
From Walker (1992).

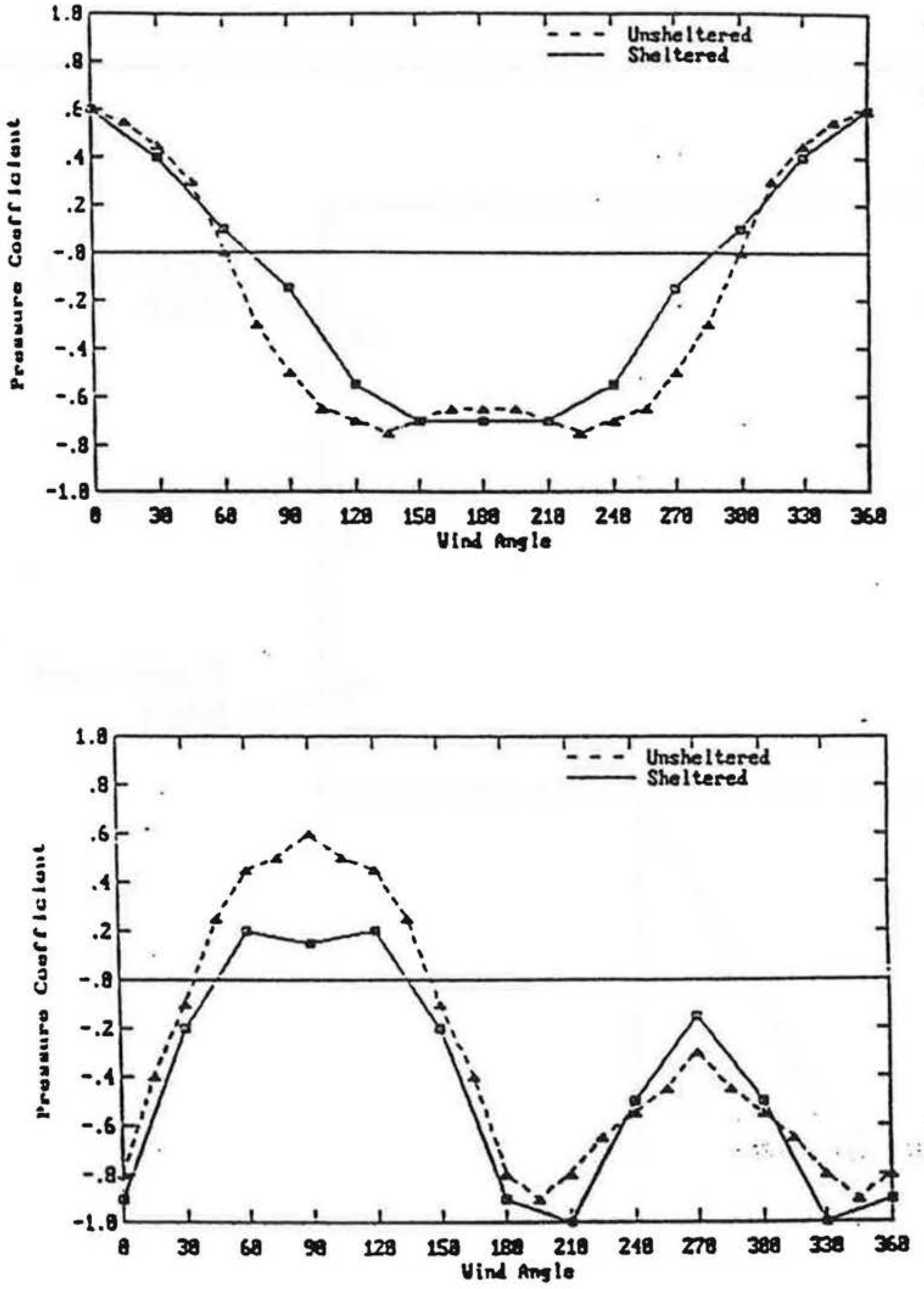


Figure 14. **Comparison of Sheltered and Unsheltered Pressure Coefficients on (a) the Front Wall and (b) the Side Wall of a Building (Wiren, 1995). From Walker (1992).**

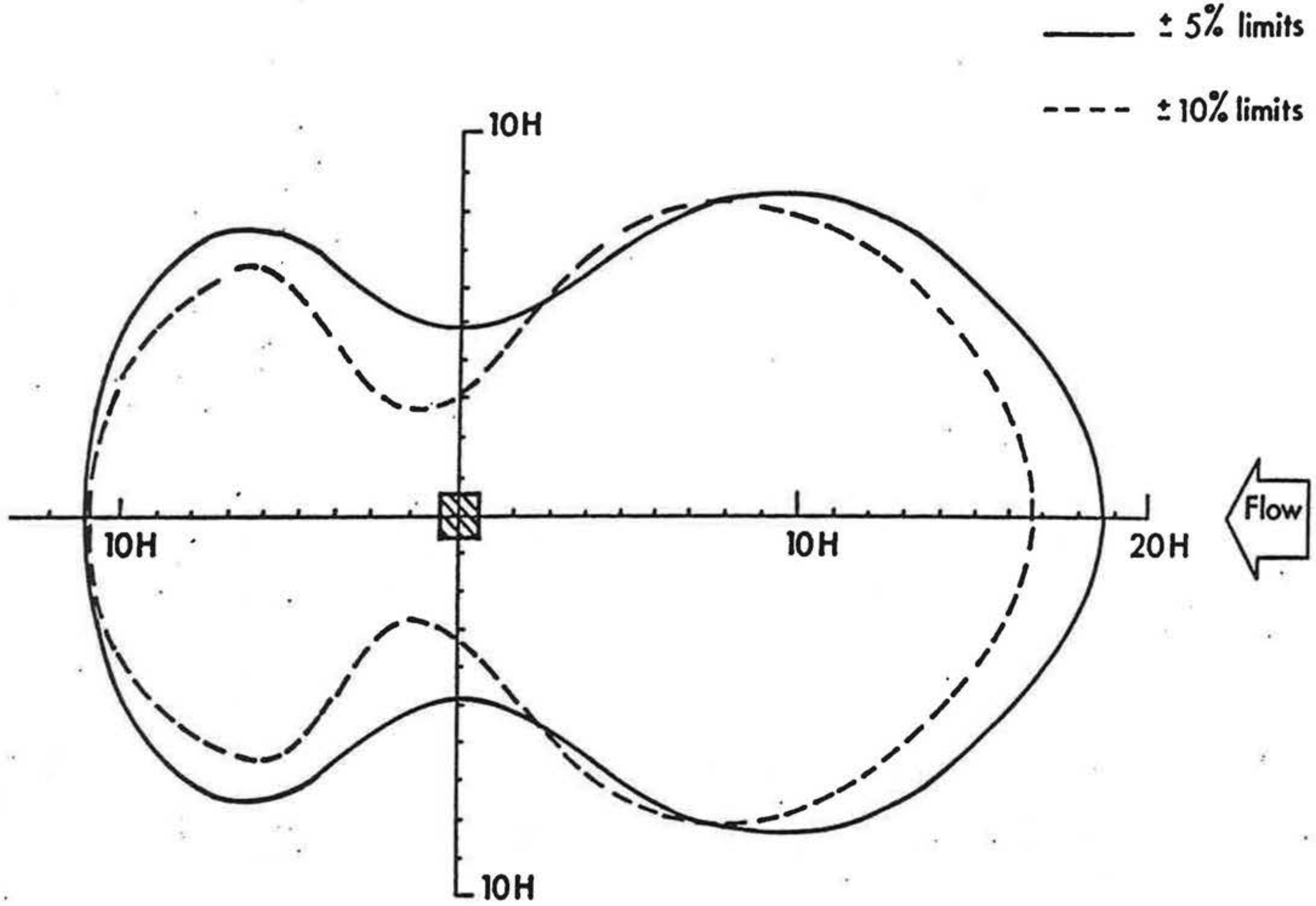


Figure 15. **Limits of the Area of Influence on the Pressure on a Cuboid Model.**
Normal Pattern. 10% Plan Area Density.
Taken from Lee et al (1979).

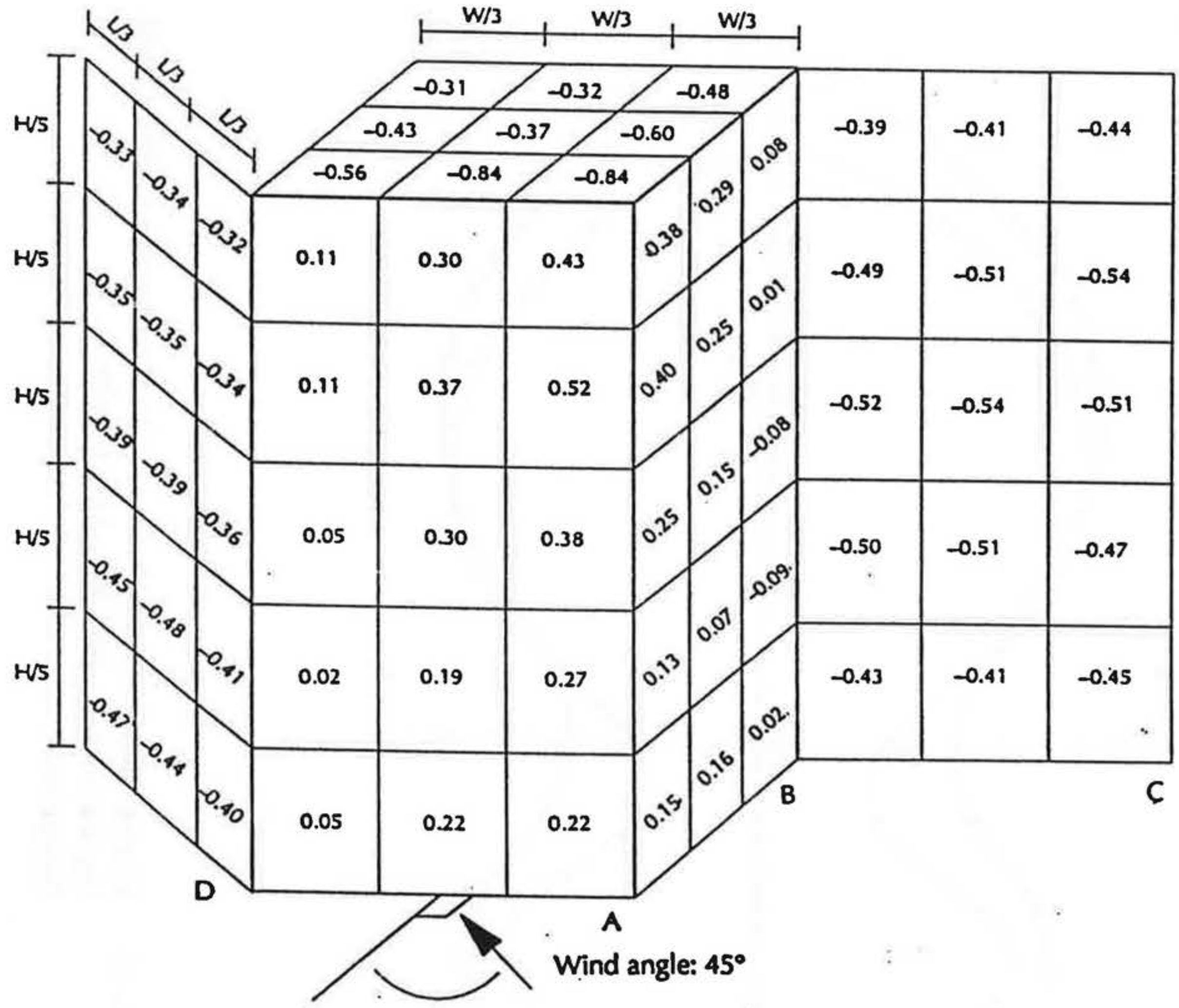


Figure 16. **Wind Pressure Coefficients on a Building with a Flat Roof, Located in a Rectangular Array of Flat Low rise Buildings of 1/6 its Height. Bowen(1976). From Orme at al (1994).**

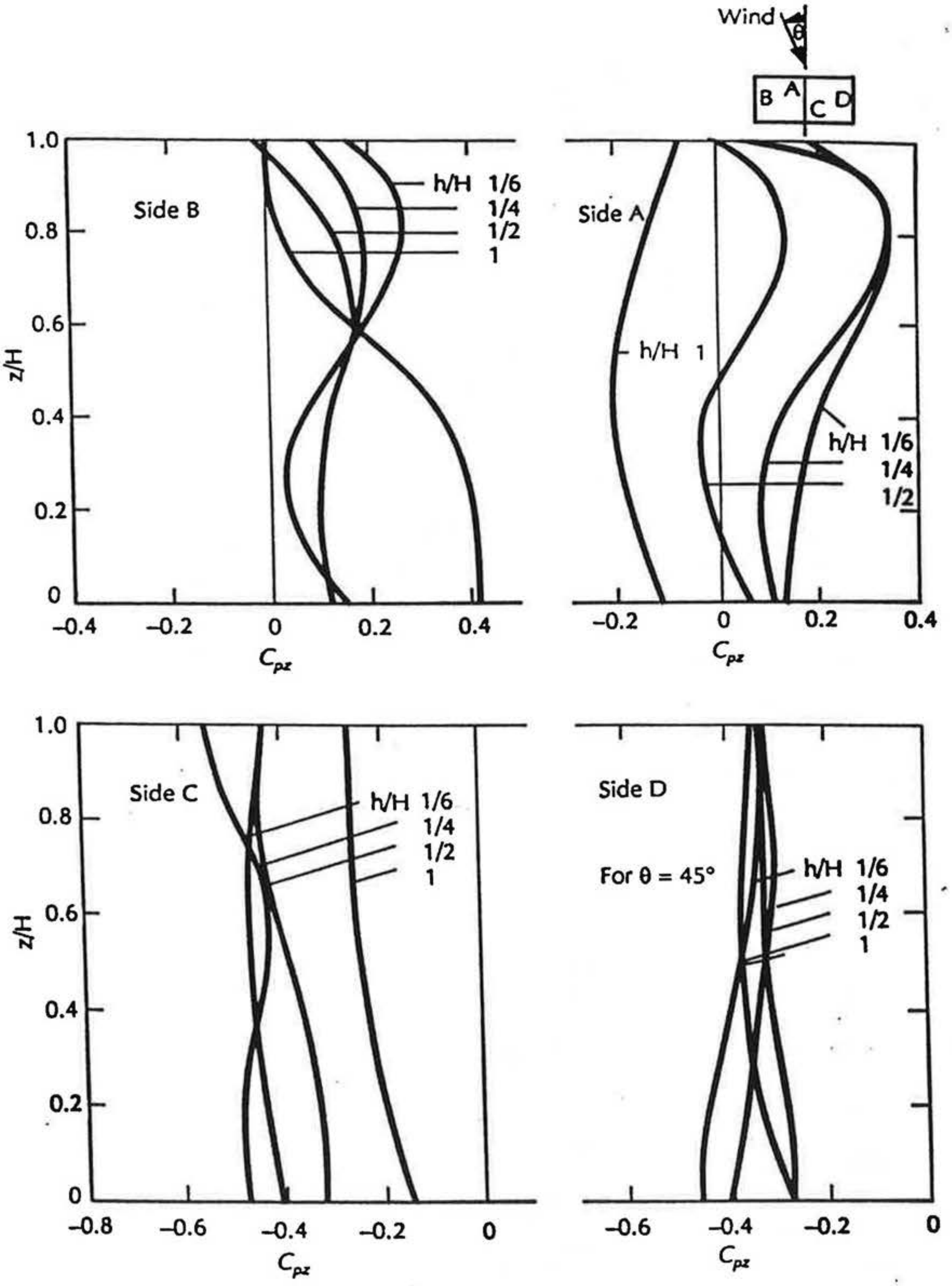


Figure 17. **Vertical Distributions of Weighted Mean Wind Pressure Coefficients C_{pz}, for Various Surrounding Obstruction Heights (Wind Angle 45°) - Figure Derived From the Data in Figure 16.**
From Orme at al (1994).

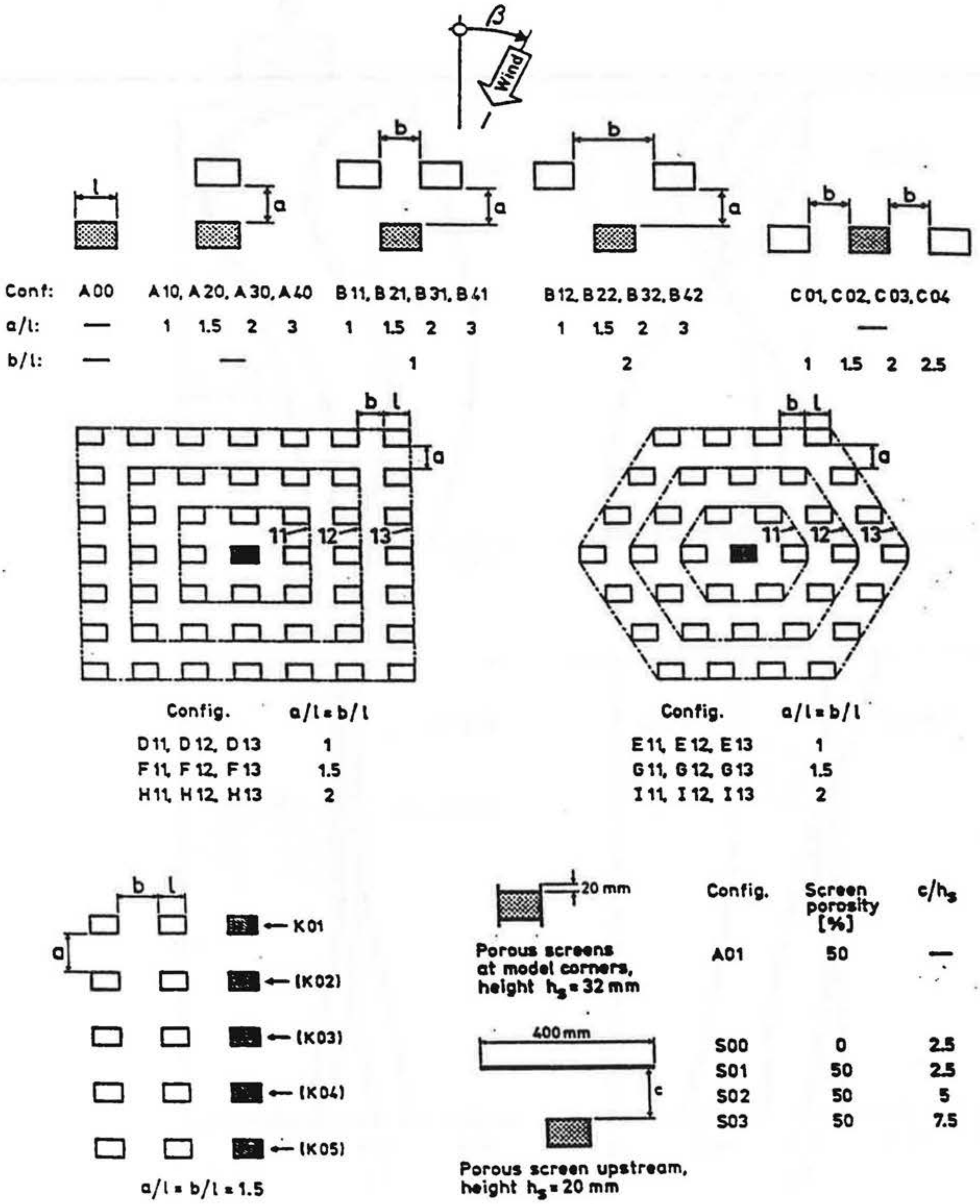


Figure 18. Model Configurations Studied for Wind Pressure Distributions over a 1:100 Scale Model of a 1½ - Storey Single Family House. From Wiren (1983).

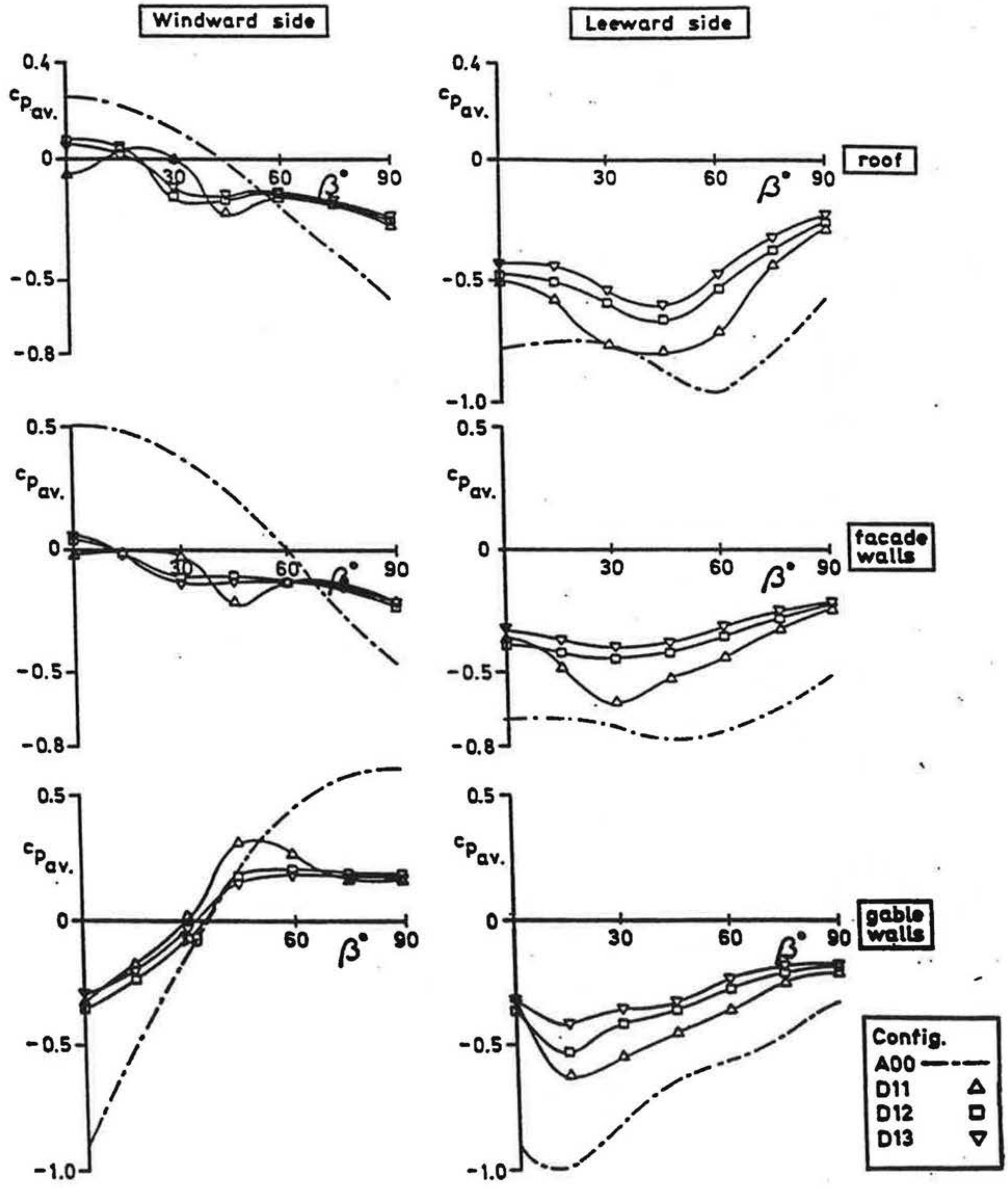


Figure 19. **Effect of Wind Angle on the Average Pressure Coefficients on Building Surfaces for Configurations D11, D12 and D13 given in Figure 18. From Wiren, (1983).**

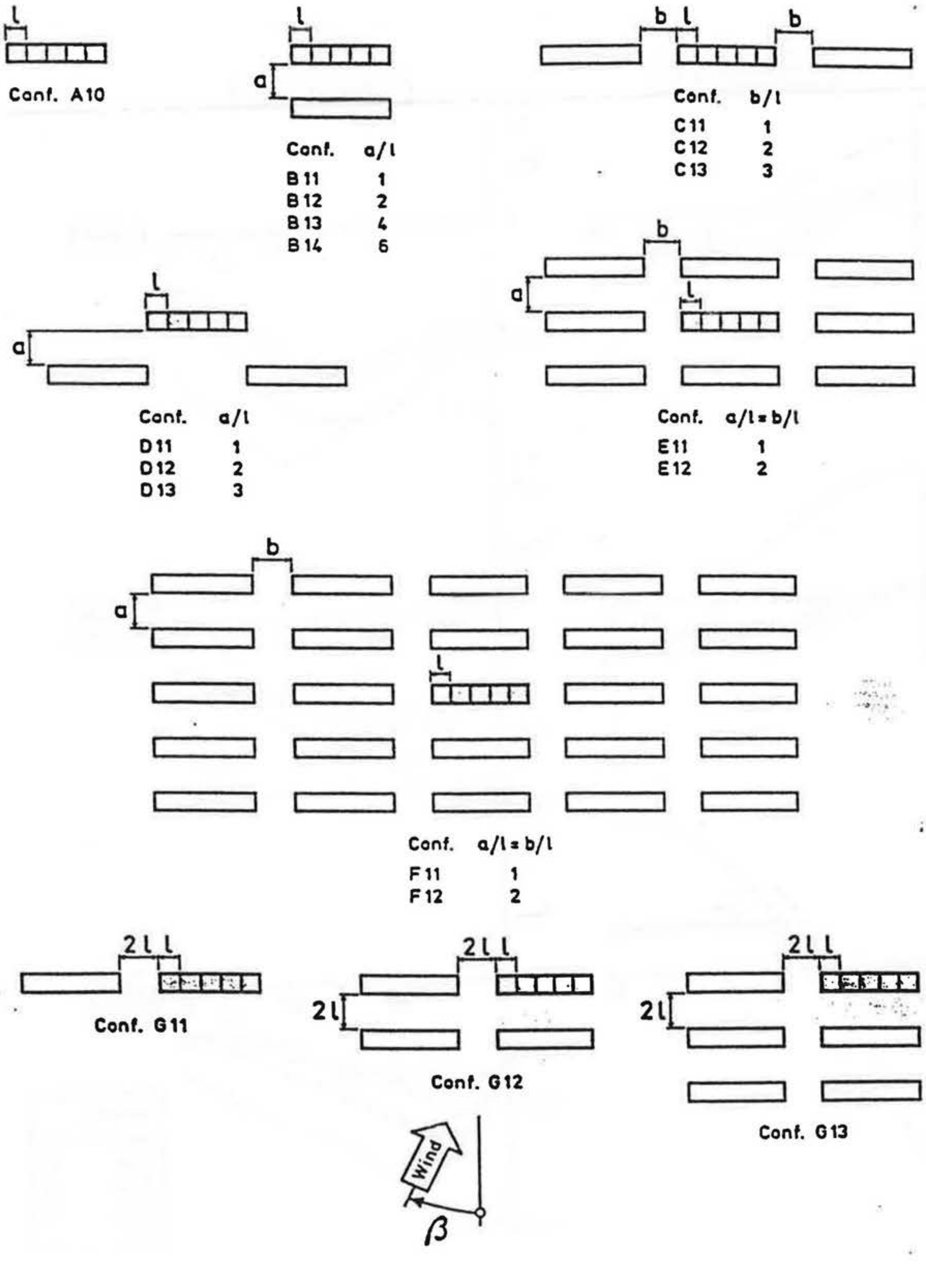
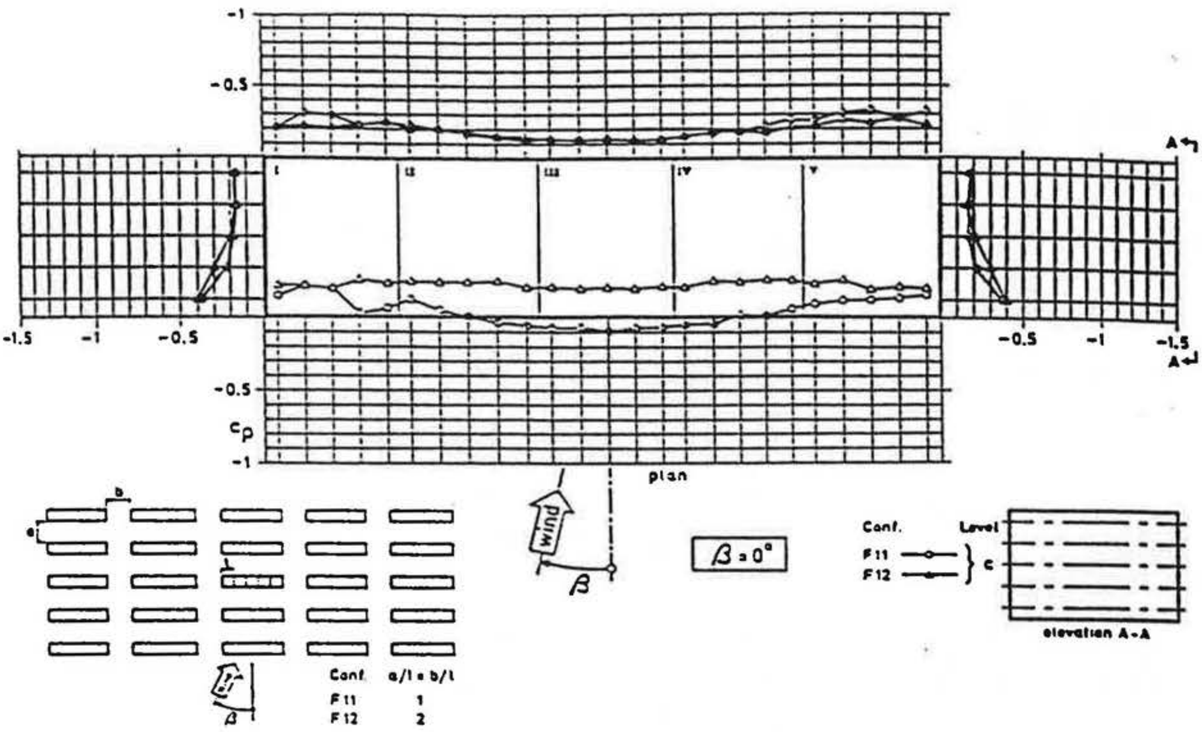


Figure 20. **Configurations Studied for Wind Pressure Distributions over a Row of Five 2 - Storey Flat-roofed Terrace Houses. From Wiren (1985).**



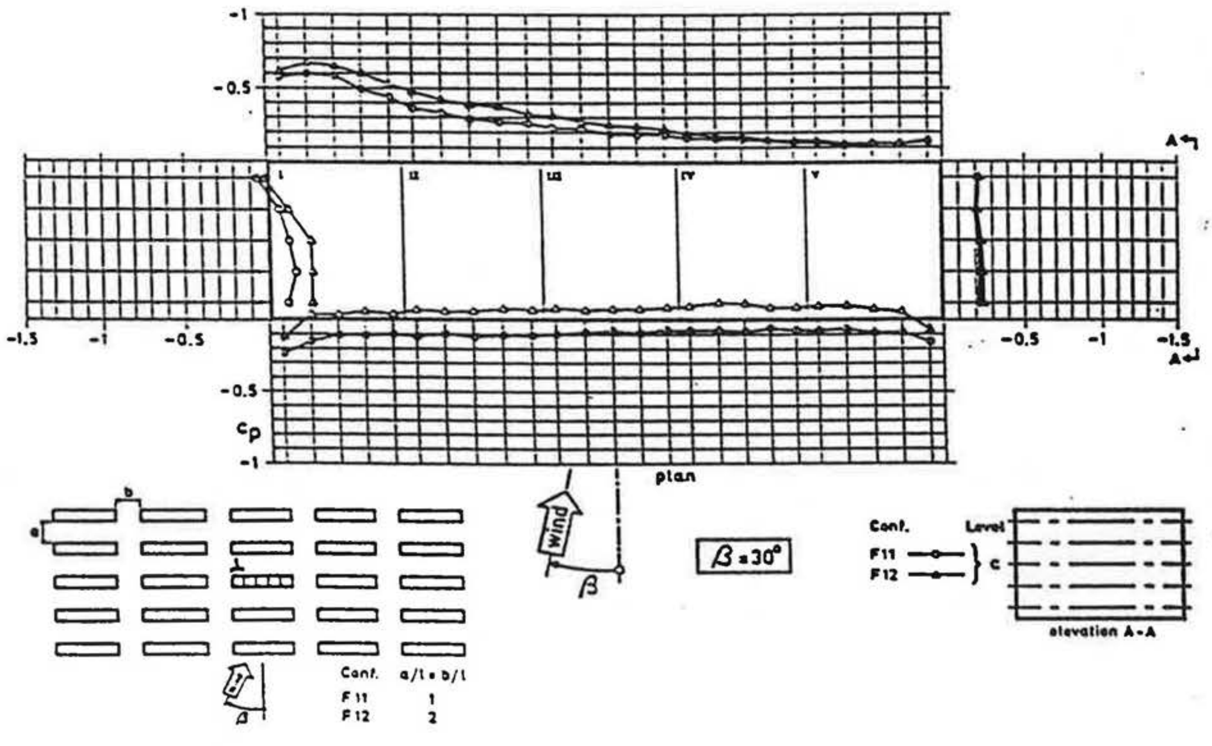


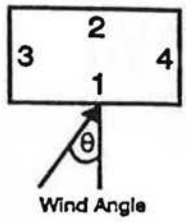
Figure 21. Average Pressure Distributions Over the Walls of a Building for Wind Angles 0° and 30° for Model Configurations F11 and F12 given in Figure 20.
From Wiren(1985).

Low-rise buildings (up to 3 storeys)

Length to width ratio: 2:1

Shielding condition: Surrounded by obstructions equal to the height of the building

Wind speed reference level: Building height



Location		Wind Angle							
		0°	45°	90°	135°	180°	225°	270°	315°
Face 1		0.06	−0.12	−0.2	−0.38	−0.3	−0.38	−0.2	0.12
Face 2		−0.3	−0.38	−0.2	−0.12	0.06	−0.12	−0.2	−0.38
Face 3		−0.3	0.15	0.18	0.15	−0.3	−0.32	−0.2	−0.32
Face 4		−0.3	−0.32	−0.2	−0.32	−0.3	0.15	0.18	0.15
Roof (<10° pitch	Front	−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
	Rear	−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Average		−0.49	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Roof (11-30° pitch)	Front	−0.49	−0.46	−0.41	−0.46	−0.4	−0.46	−0.41	−0.46
	Rear	−0.4	−0.46	−0.41	−0.46	−0.49	−0.46	−0.41	−0.46
Average		−0.45	−0.46	−0.41	−0.46	−0.45	−0.46	−0.41	−0.46
Roof (>30° pitch)	Front	0.06	−0.15	−0.23	−0.6	−0.42	−0.6	−0.23	−0.15
	Rear	−0.42	−0.6	−0.23	−0.15	−0.06	−0.15	−0.23	−0.6
Average		−0.18	−0.4	−0.23	−0.4	−0.18	−0.4	−0.23	−0.4

Figure 22. **An Example of a Summary of all Pressure Distribution Data Obtained by Bowen (1976) and Wiren (1983, 1985).**
From Orme et al(1994).

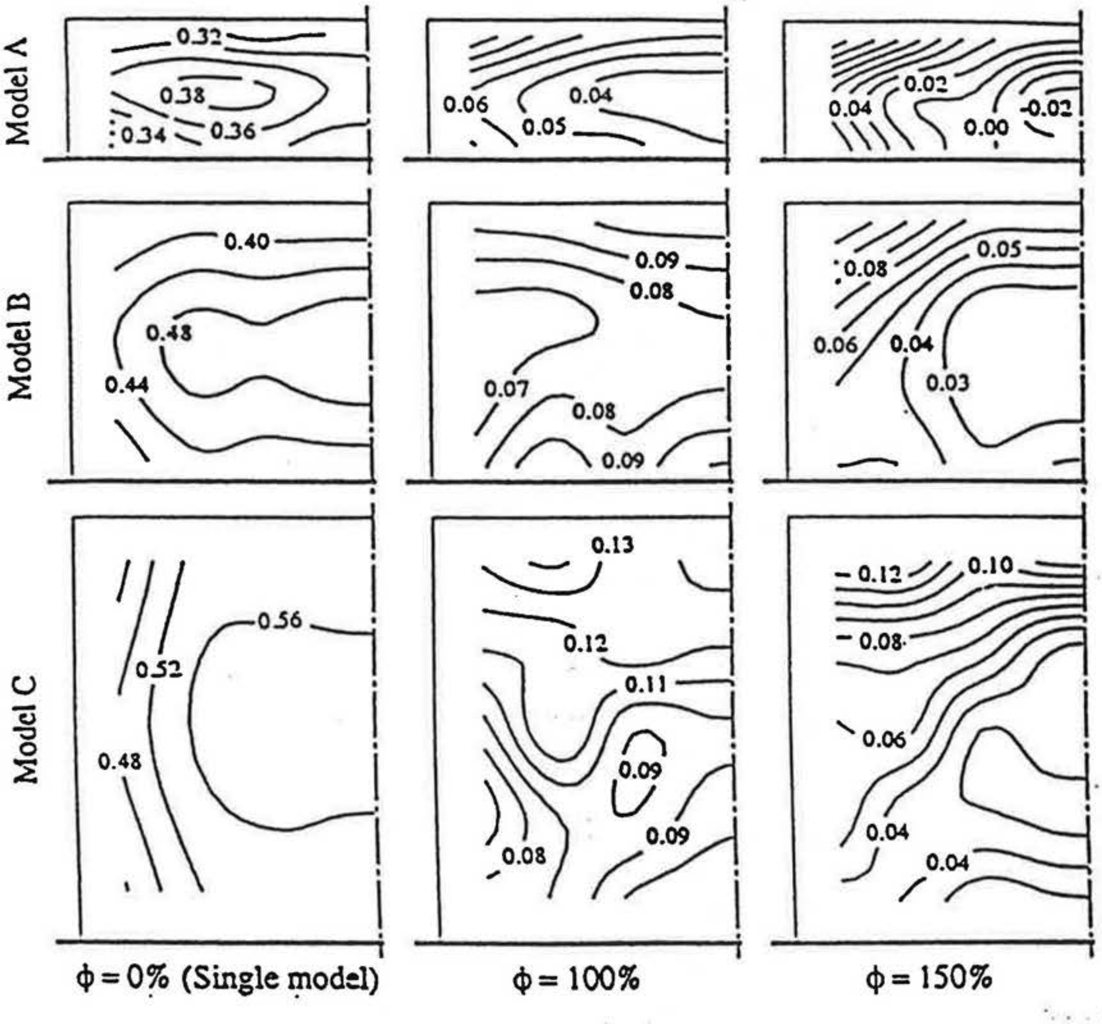


Figure 23. **Typical Surface Pressure Distributions Over Low-rise Apartments in Normal Grid Layouts.**
From Tsutsumi et al (1992).

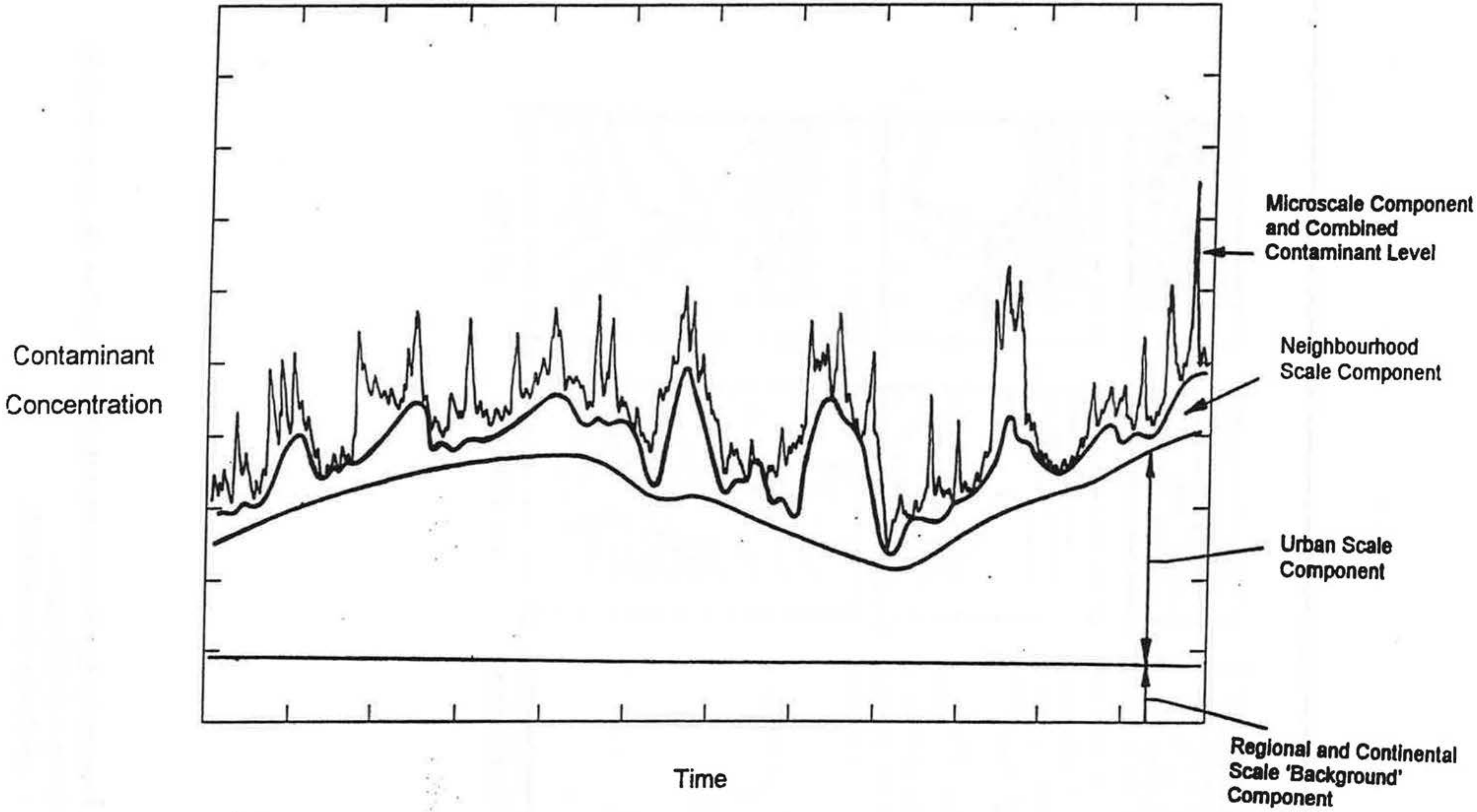


Figure 24. **Hypothetical Example of the Contributions of Contaminants from Different Source Regimes.**

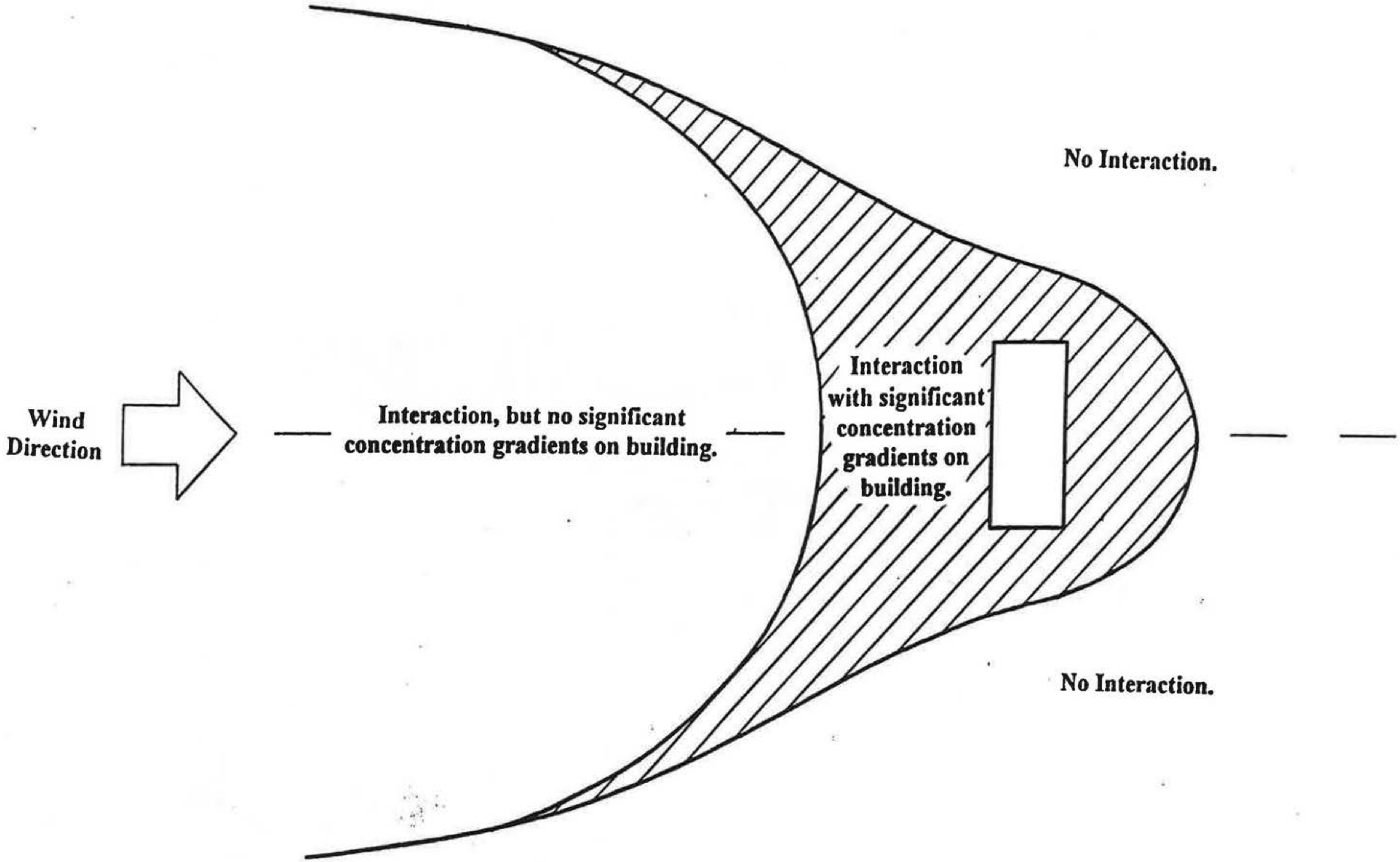


Figure 25. Diagram of the Different Regimes of Dispersing Pollutant Plume Interaction with a Building.

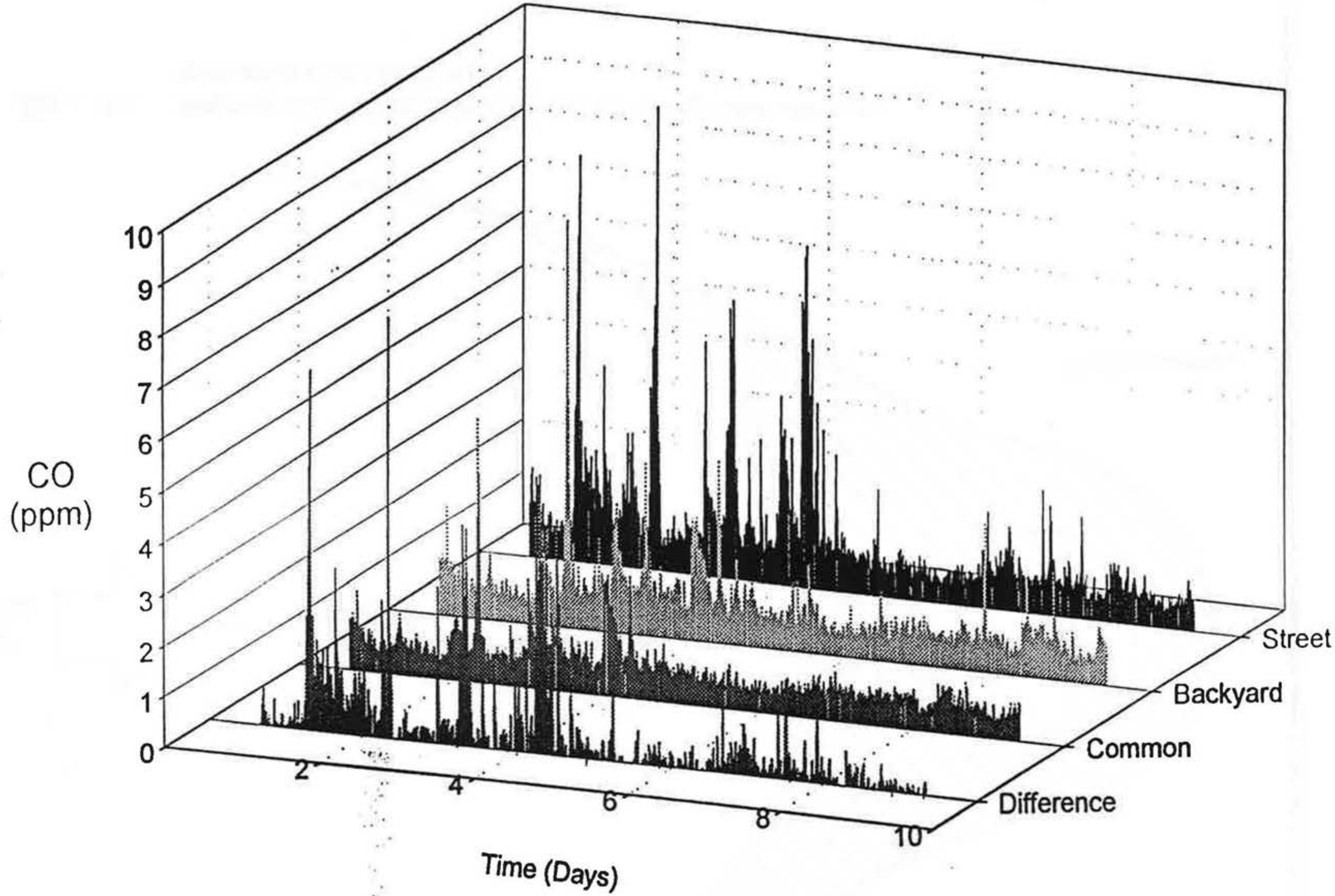


Figure 26. **Measurements of CO on the Two Sides of a Building next to a Busy Street.**
From Kruger (199?).

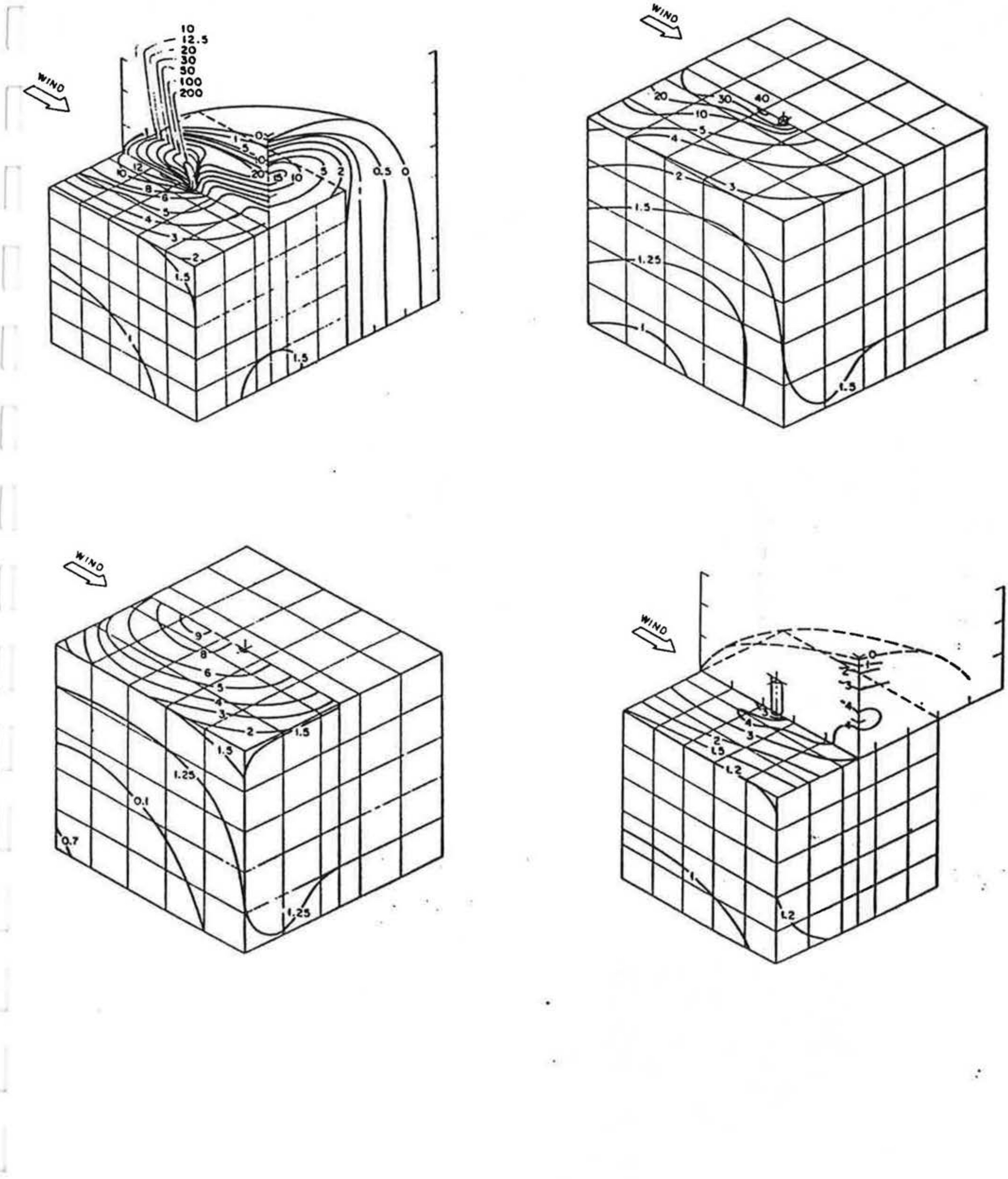


Figure 27. **Concentration Contours on a Single Building Due to a Flush Vent on the Roof. From Halitsky(1963).**

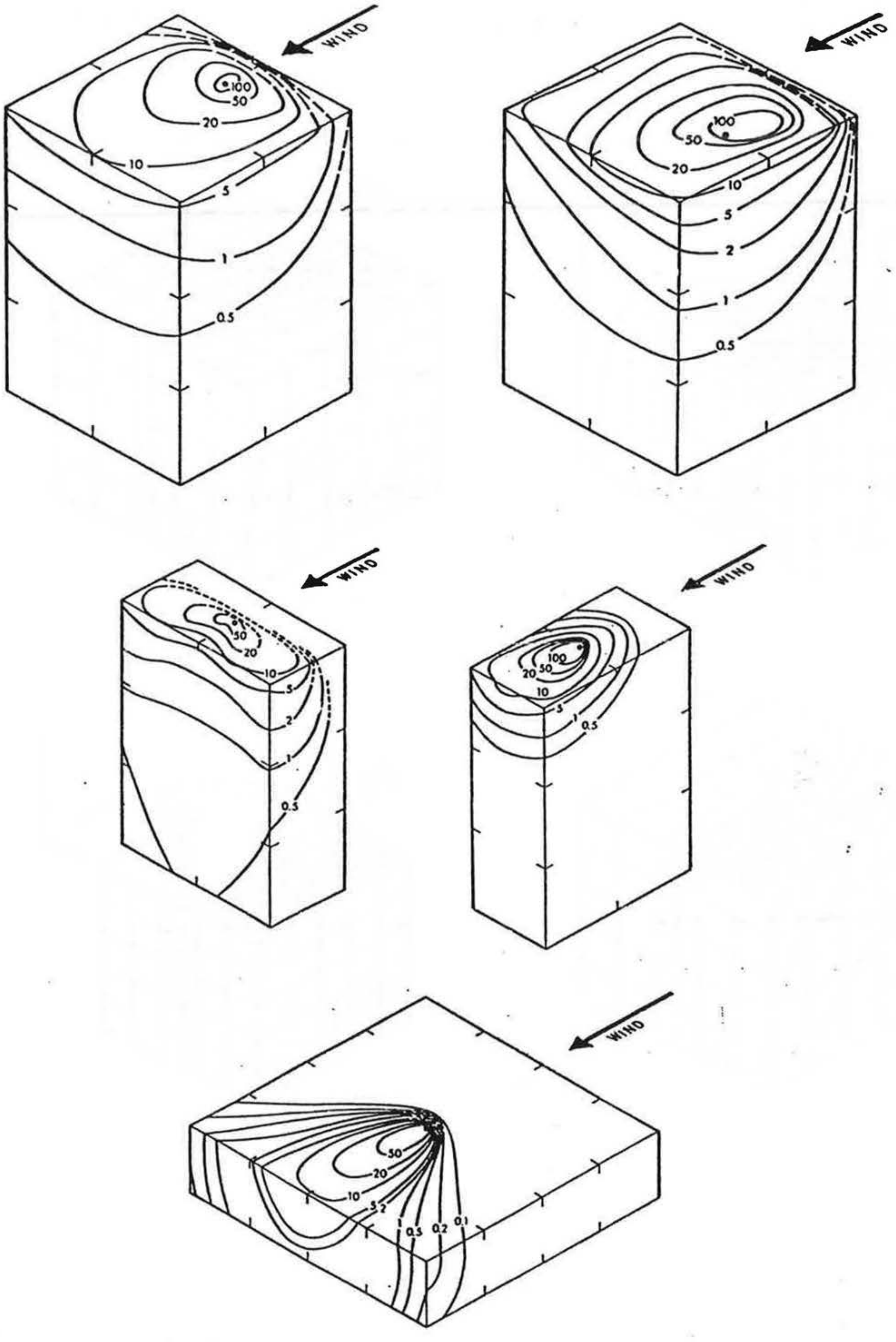


Figure 28. **Concentration Contours on a Single Building Due to a Flush Vent on the Roof. From Wilson(1976).**

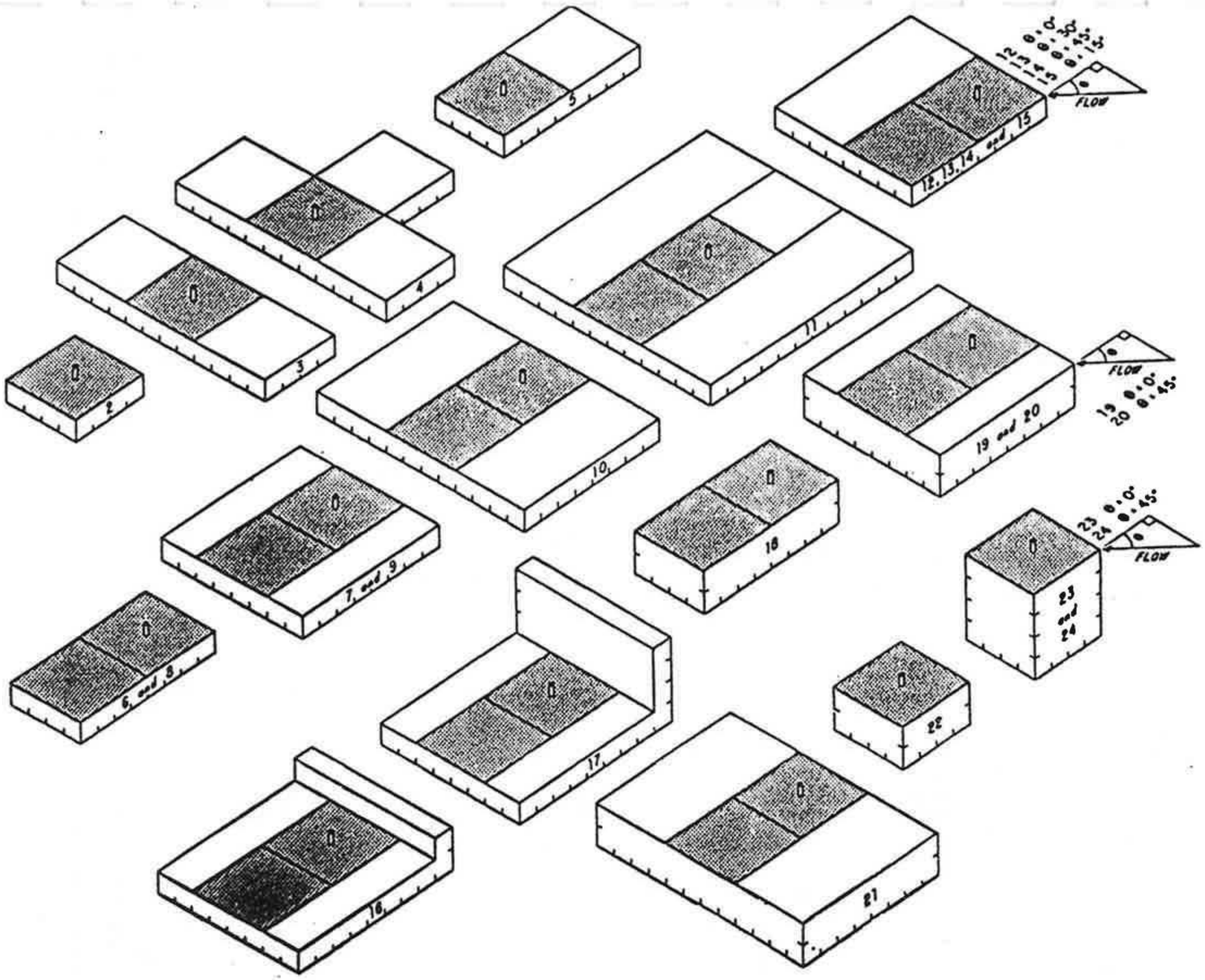


Figure 29. Range of Building Shapes Investigated by Wilson and Winkel (1982), Together with Some Examples of the Experimental Measurements of Contaminant Concentrations on the Building from Elevated Sources.

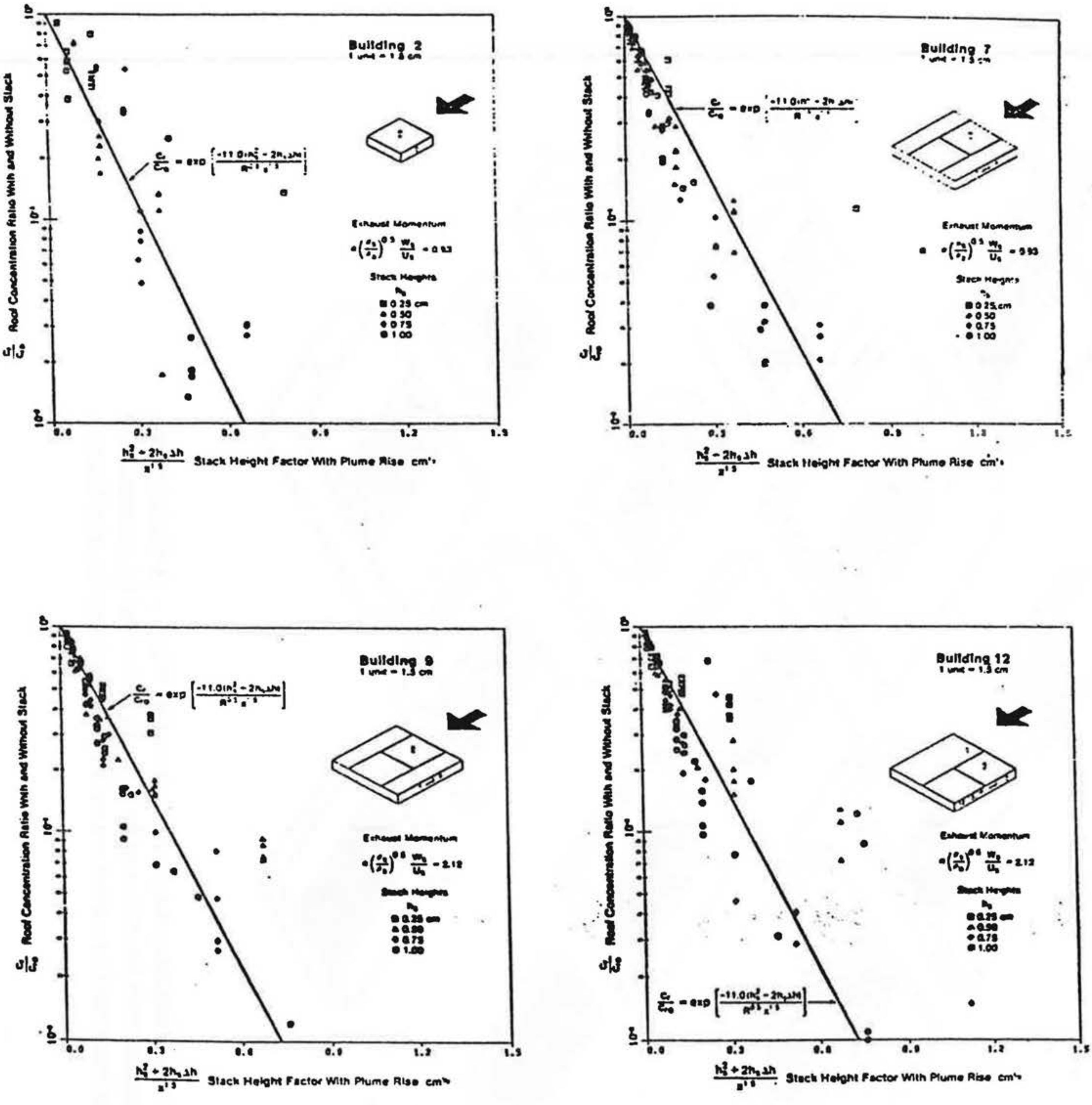


Figure 30. **Some Results of Wilson and Winkels's (1982) Experiments on Concentrations on a Building from Elevated Sources on the Building.**

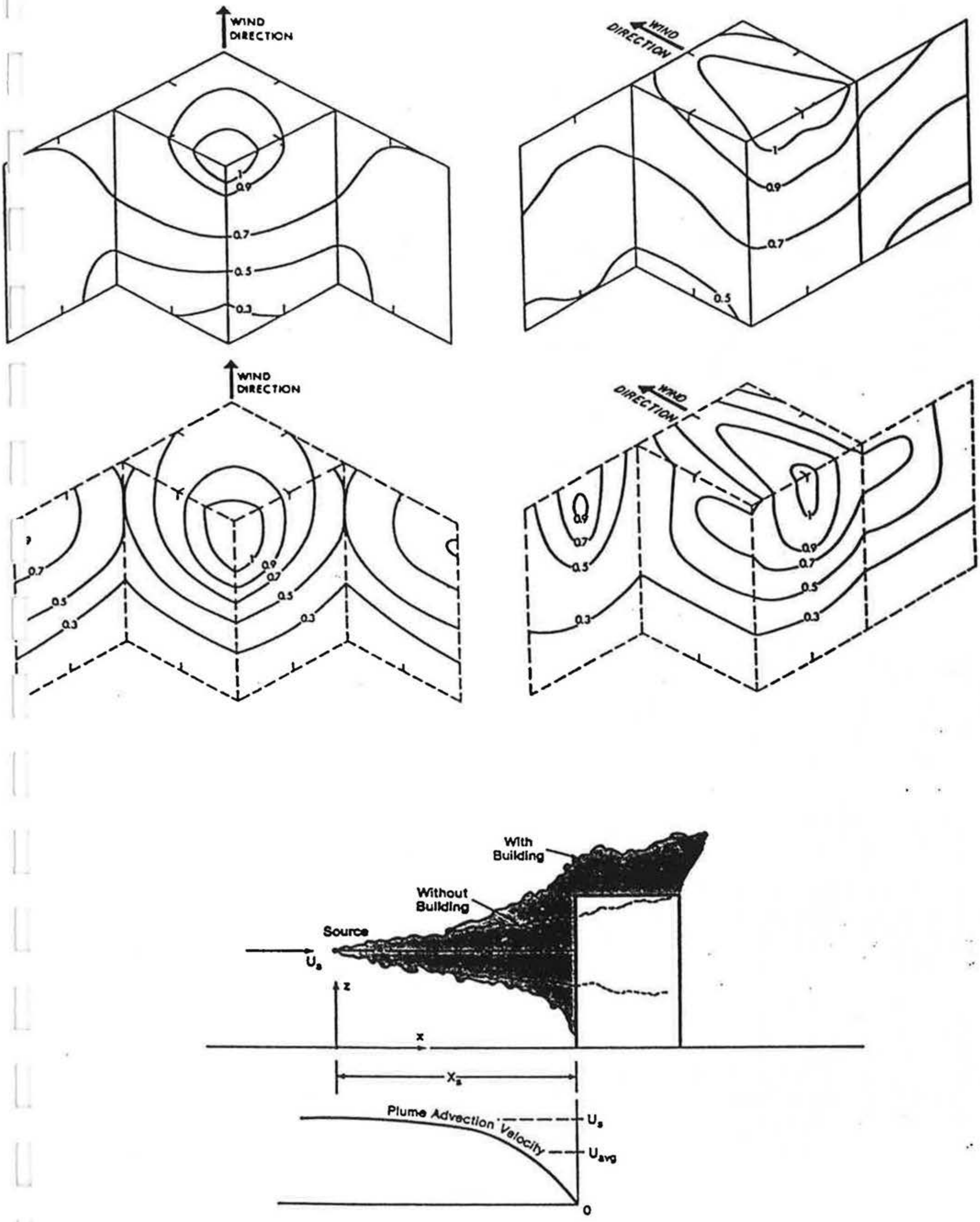


Figure 31. Concentration Patterns on a Building Due to an Impacting Upwind Source. From Wilson and Netterville(1978), as Reproduced by Wilson and Britter (1982).

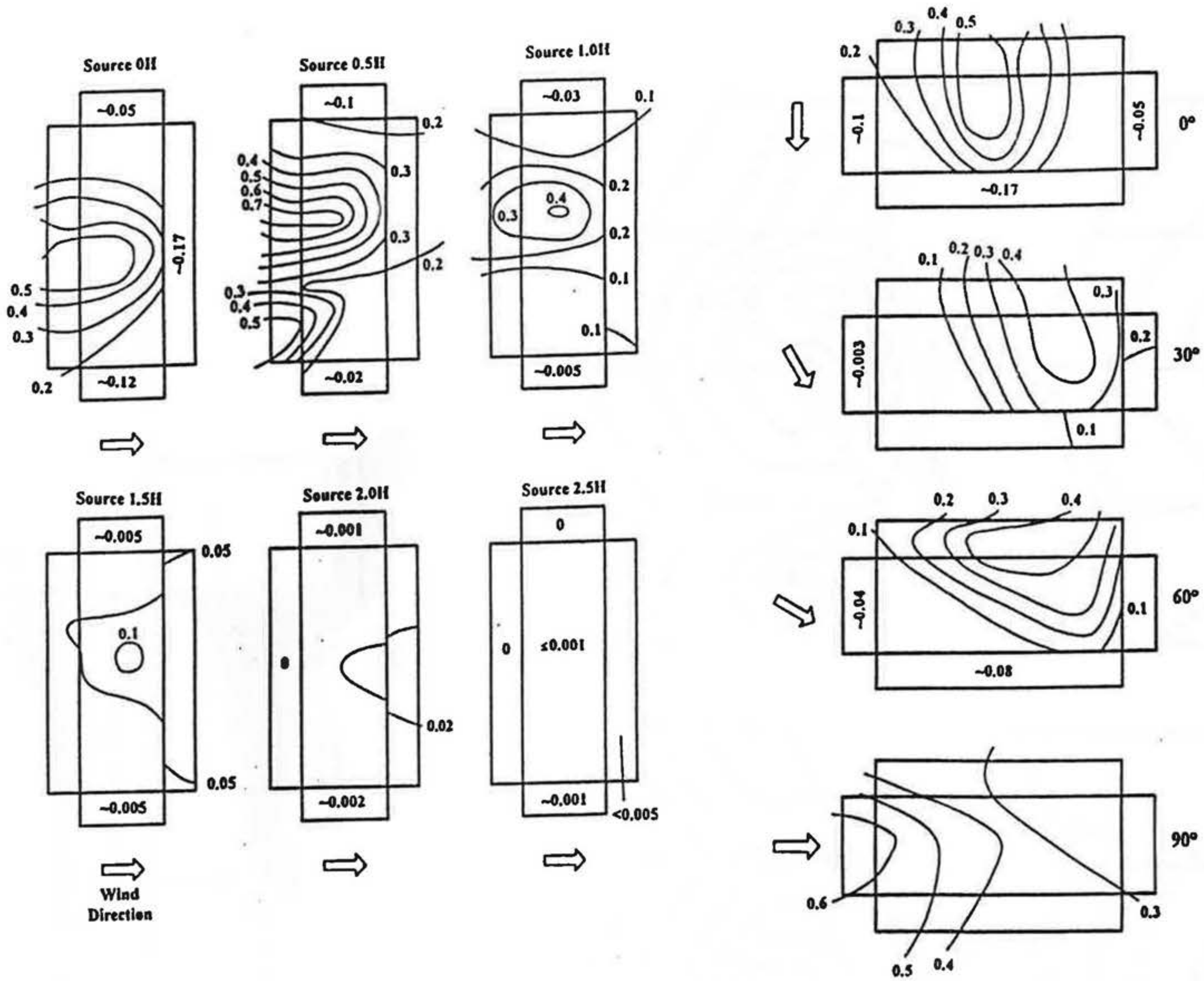


Figure 32. **Concentration Patterns on a Low Wide Building from Upwind Sources. From Hall et al (1996c),**

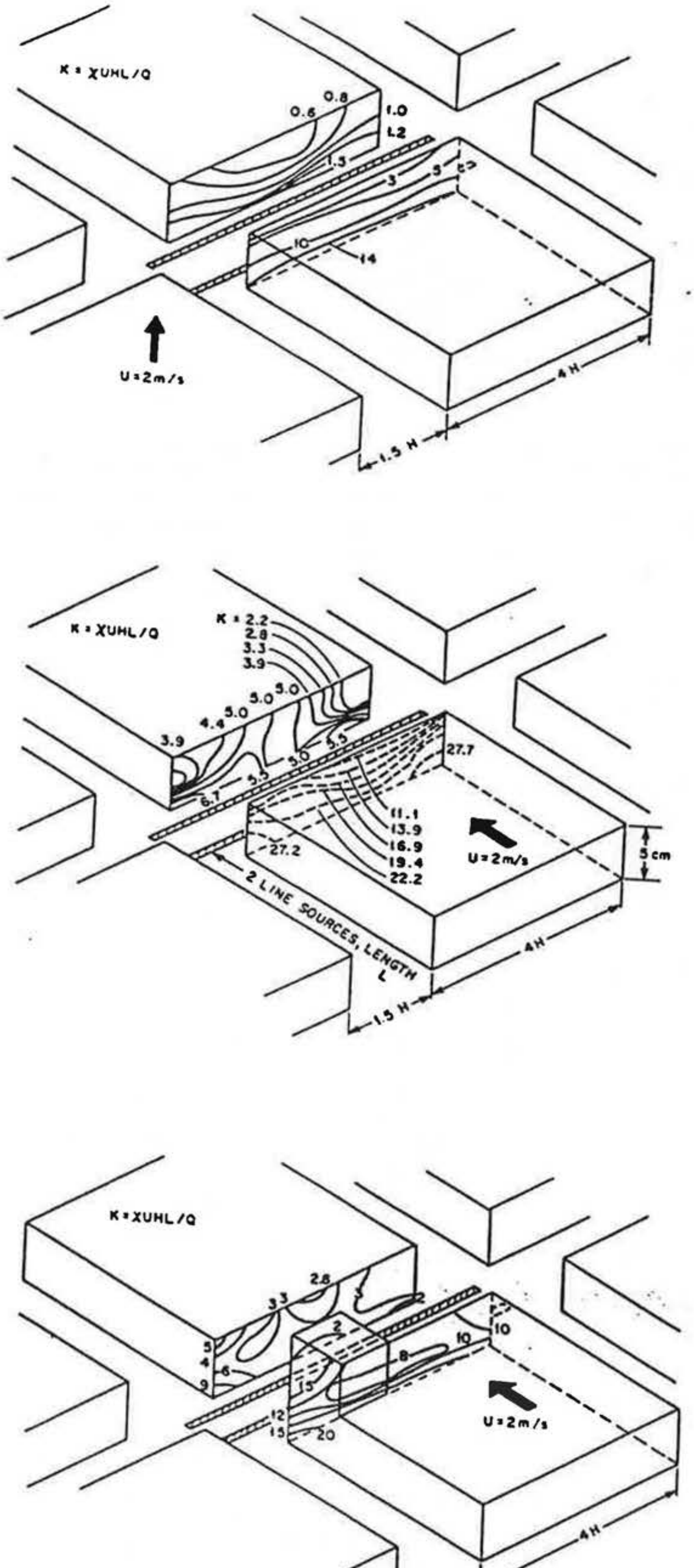


Figure 33. **Concentration Patterns on Building Blocks in an Urban Array, for Two Wind Directions and with a Modified Block Shape.**
From Cermak et al (1974).

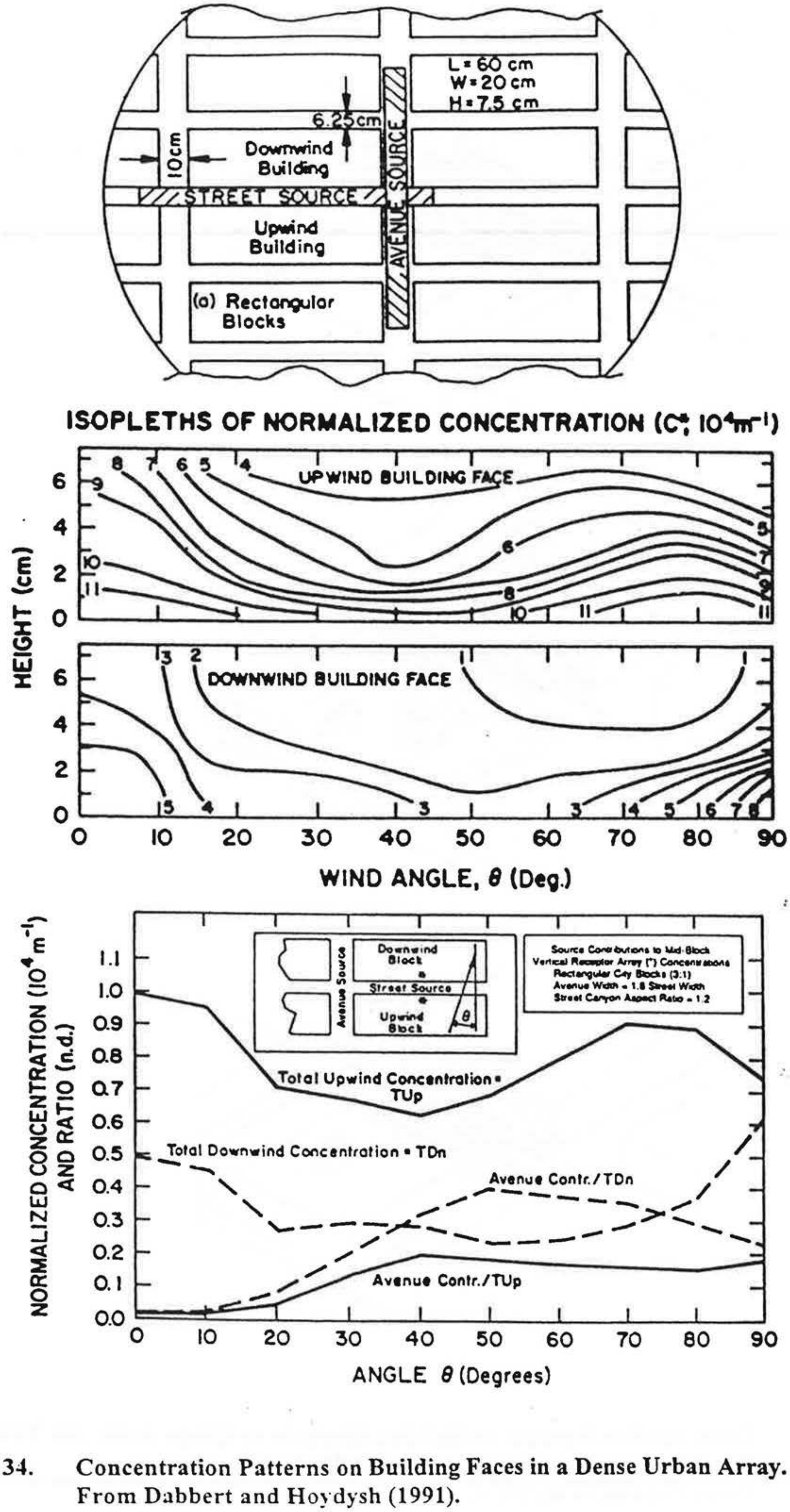


Figure 34. Concentration Patterns on Building Faces in a Dense Urban Array. From Dabbert and Hoydysh (1991).

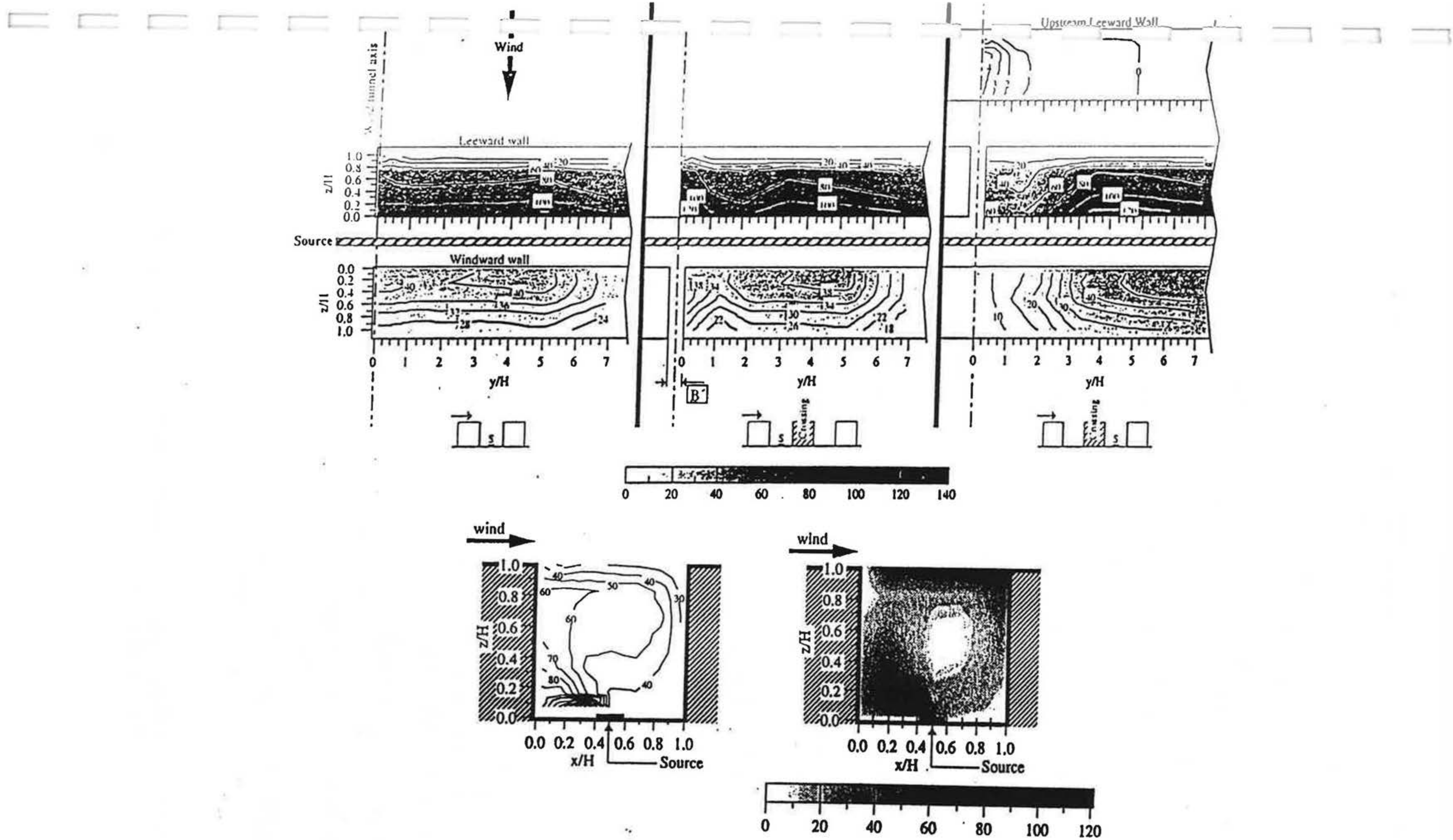


Figure 35. Concentration Patterns in the Street Cross Section and on the Building Faces in a Two-Dimensional Urban Canyon.
From Pavageau et al (1996).

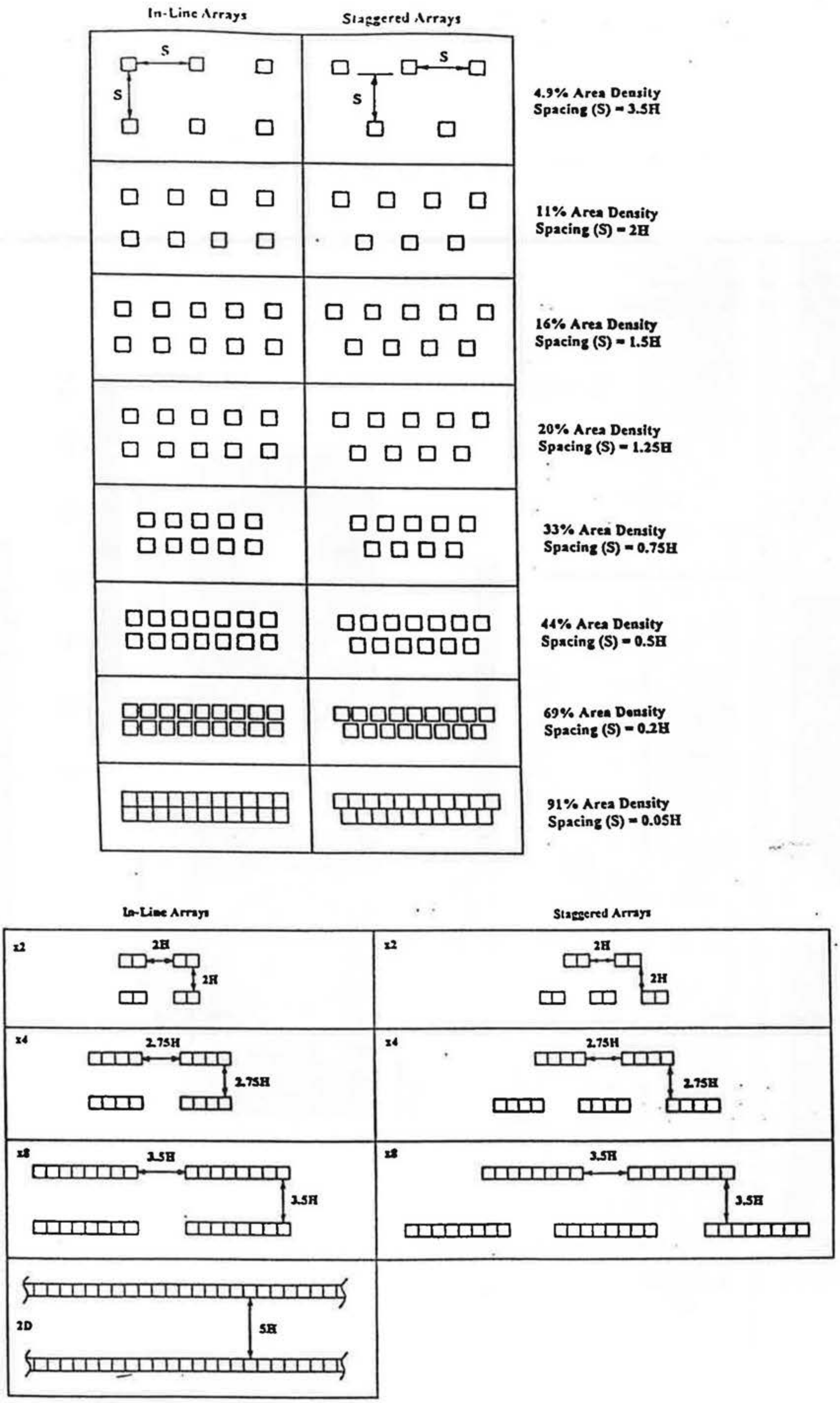


Figure 36. **Urban Array Layouts Used in the BRE Experimental Programme. From Hall et al (1996d).**

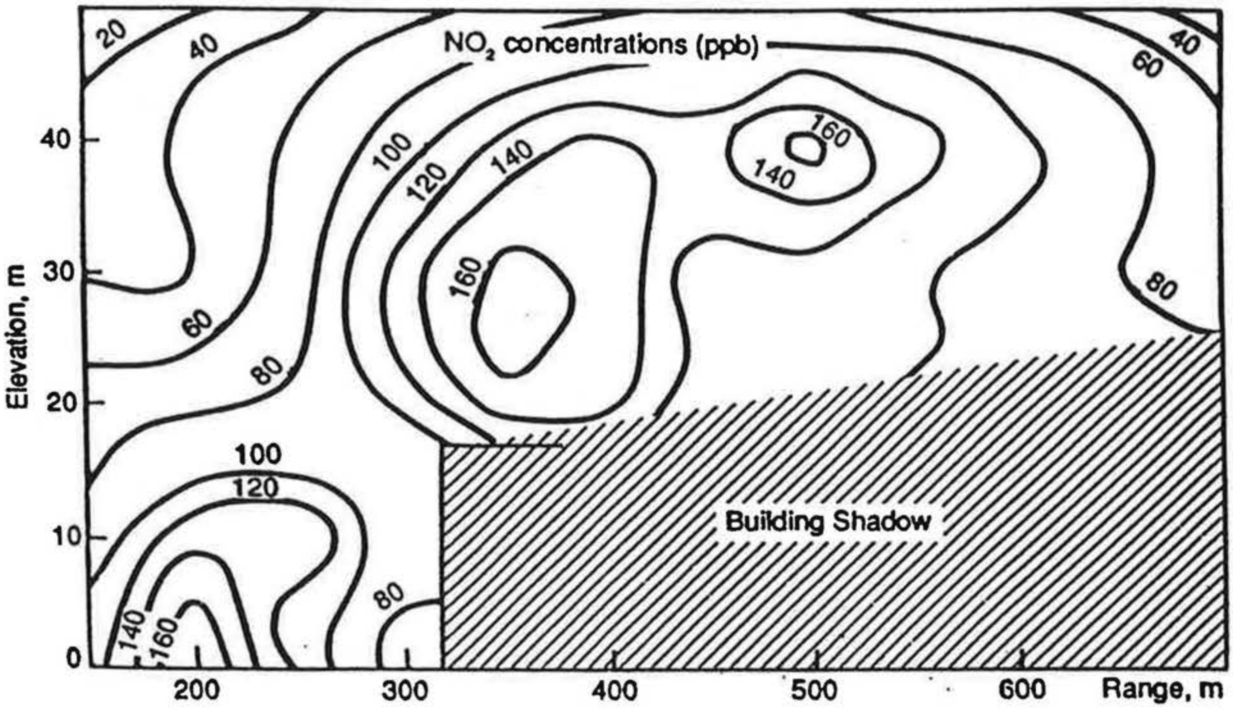


Figure 37. **Remotely Sensed Contours in a London Street with Dense Traffic. From QUARG (1993).**